Lecture 12

Frequency-domain EM with inductive sources

GEOL 4397: Electromagnetic Methods for Exploration
GEOL 6398: Special Problems

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Oct. 11th, 2018

UNIVERSITY of HOUSTON
YOU ARE THE PRIDE
EARTH AND ATMOSPHERIC SCIENCES

Announcement

- No in-class meetings next week
  - Class not canceled
  - You have work to do

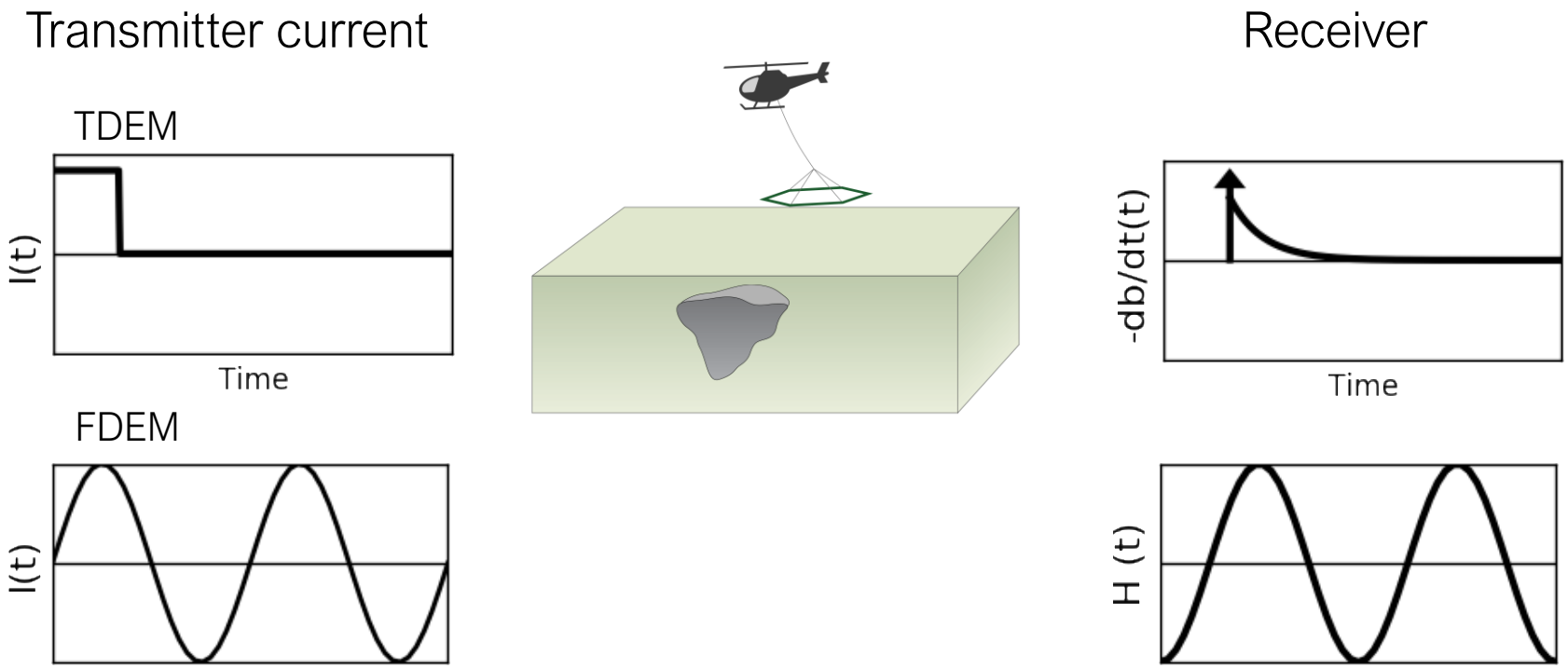
- Due date for Lab 4 extended to 4 pm on Oct 23rd

Outline

- FDEM in homogeneous halfspace
- FDEM in layered Earth
- Shielding problem
- Case history: Bookpurnong
- Case history: Landslide
- Things to do for next week
- Literature search

EM with Inductive Sources

- Induction principles are the same for
  - TDEM: Time domain EM
  - FDEM: Frequency domain EM



Credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Vertical Magnetic Dipole over a halfspace (FDEM)

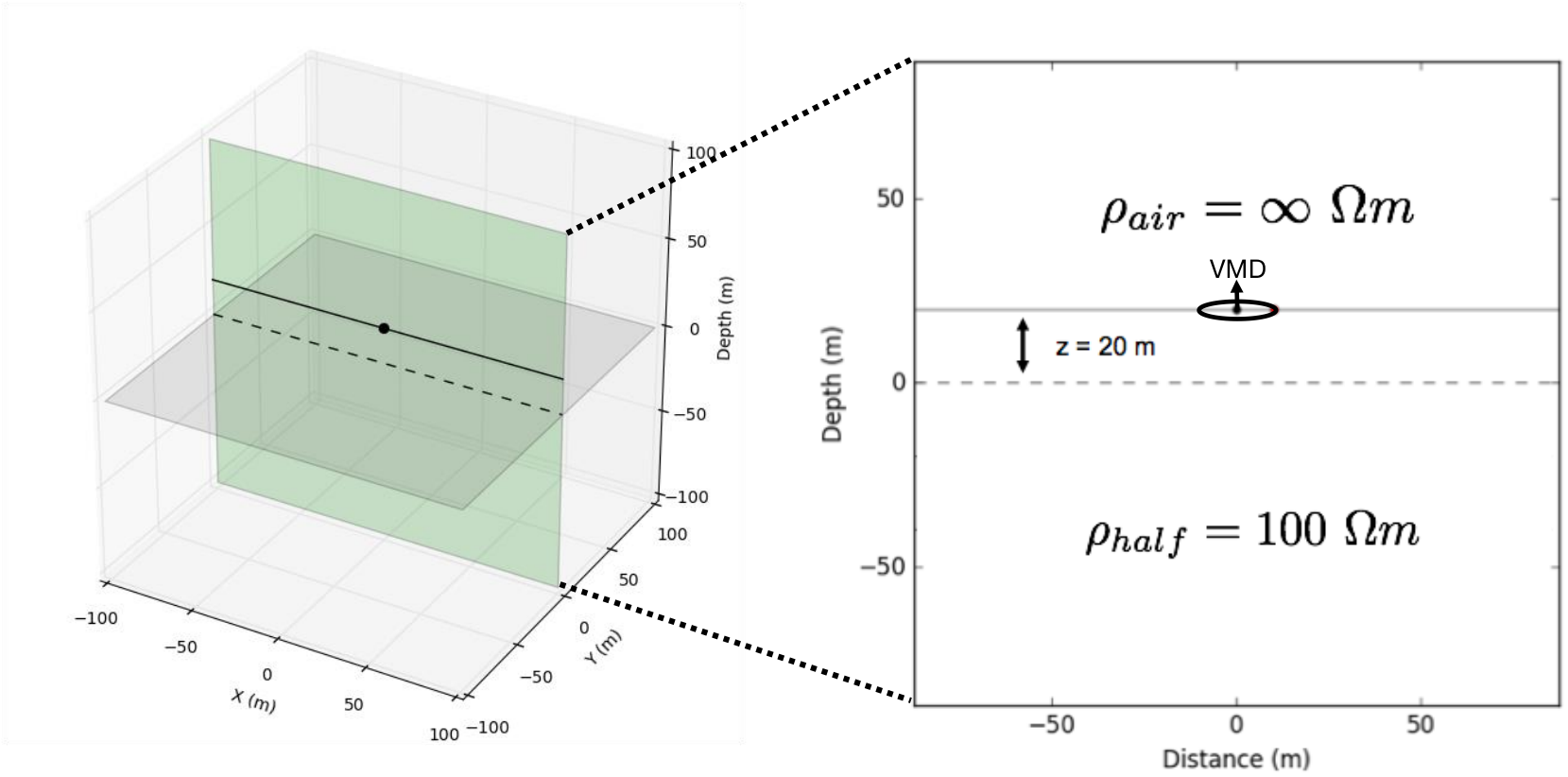
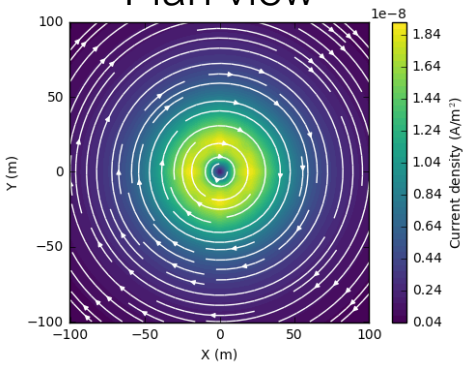


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

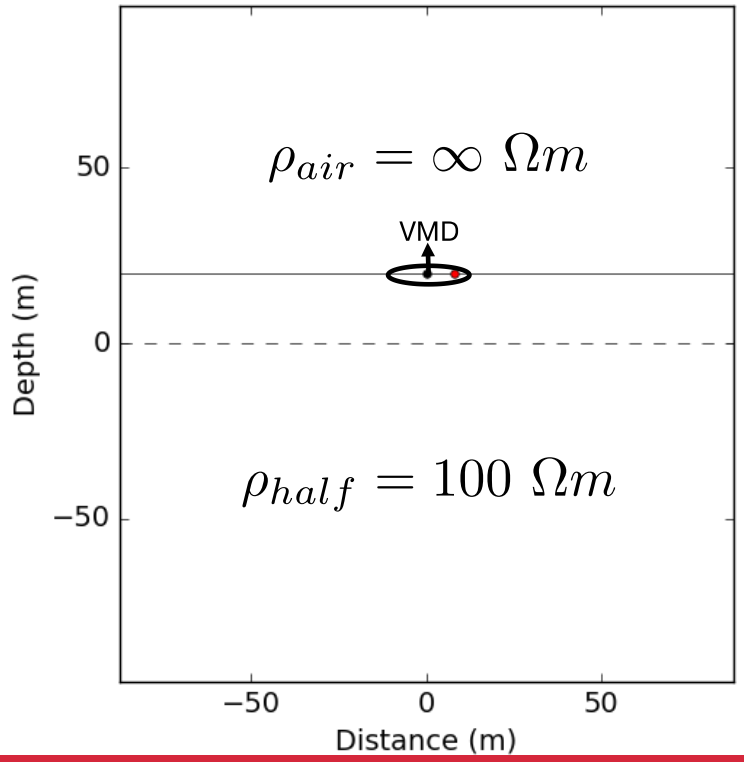
Current Density

- Frequency = 10 kHz
- Currents in the earth flow in planes parallel to the Tx

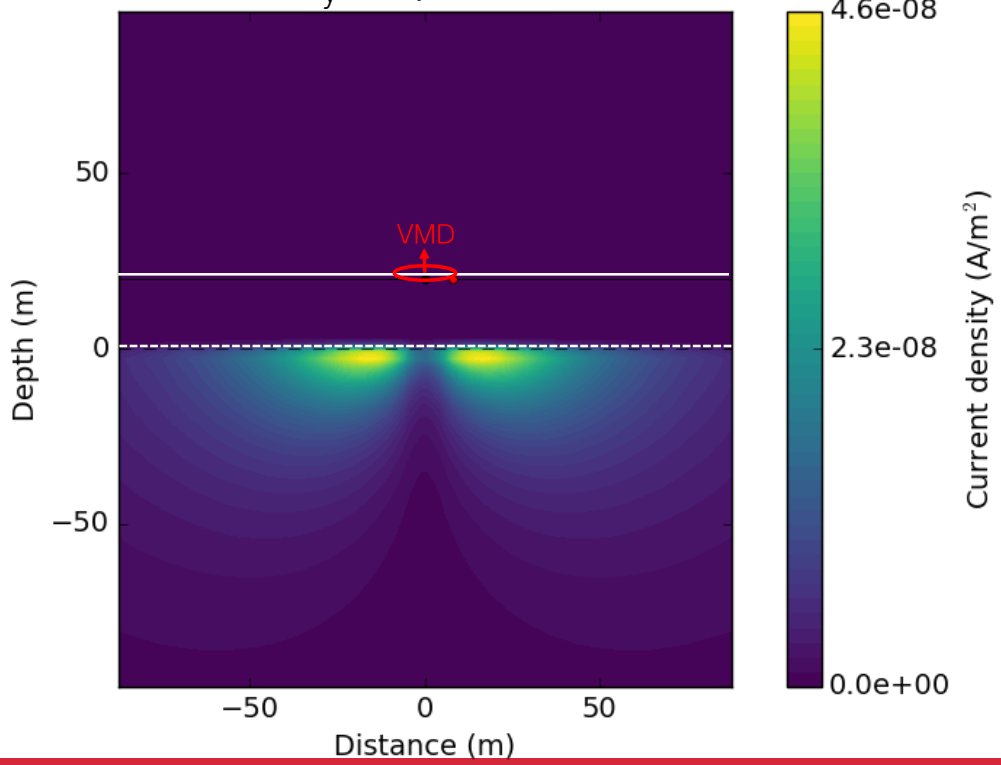
Plan view



Geometry

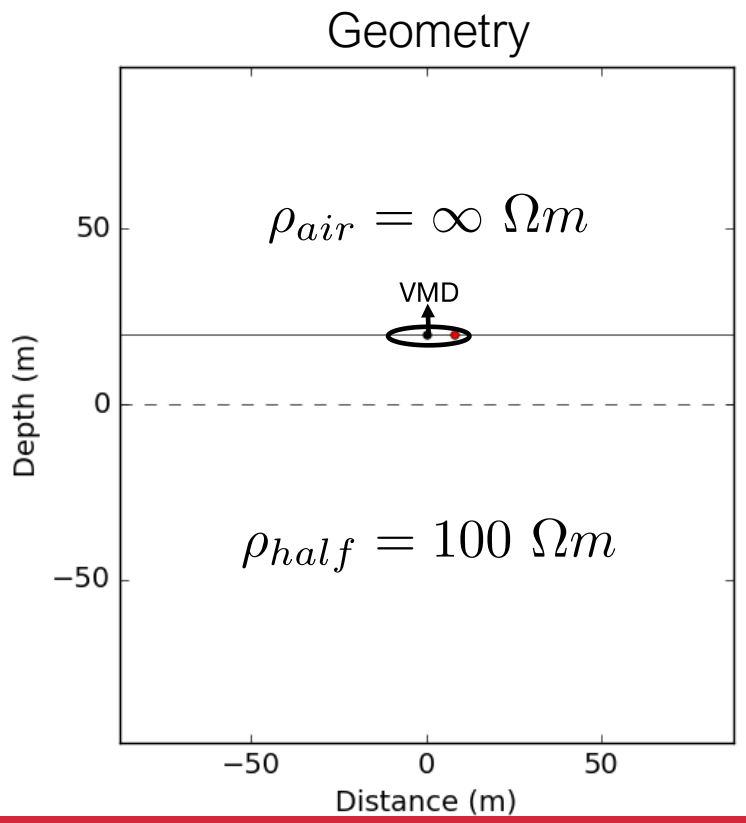


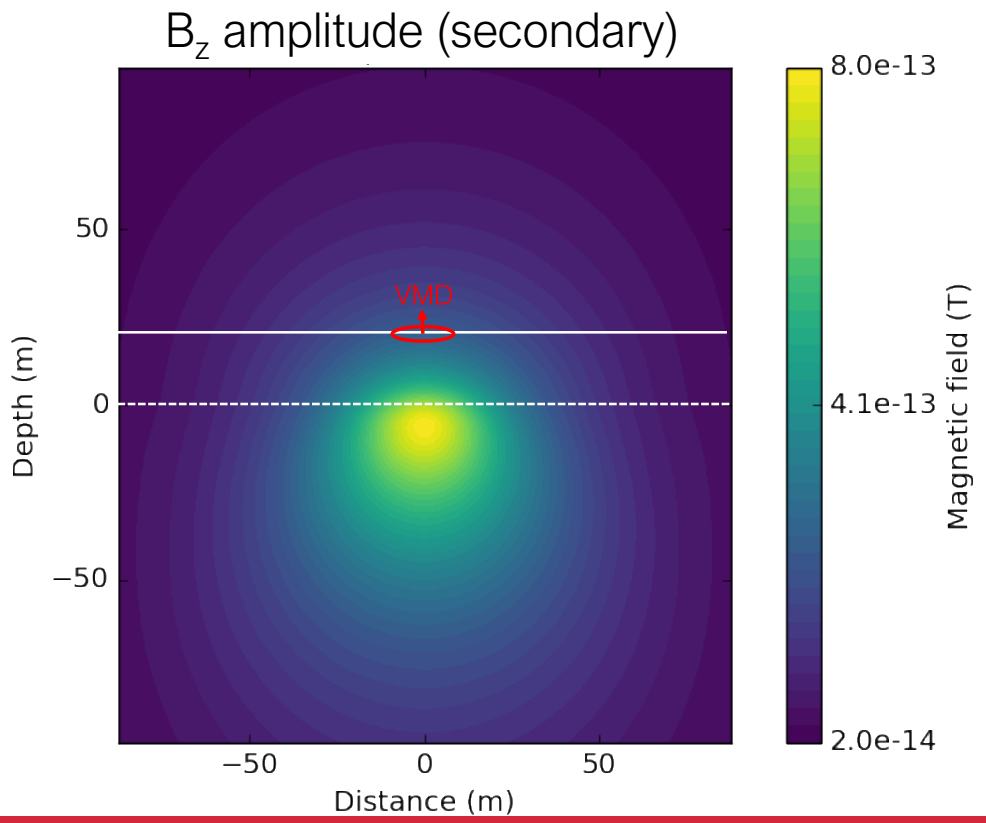
J_y amplitude



Secondary Magnetic Flux Density

- Frequency = 10 kHz

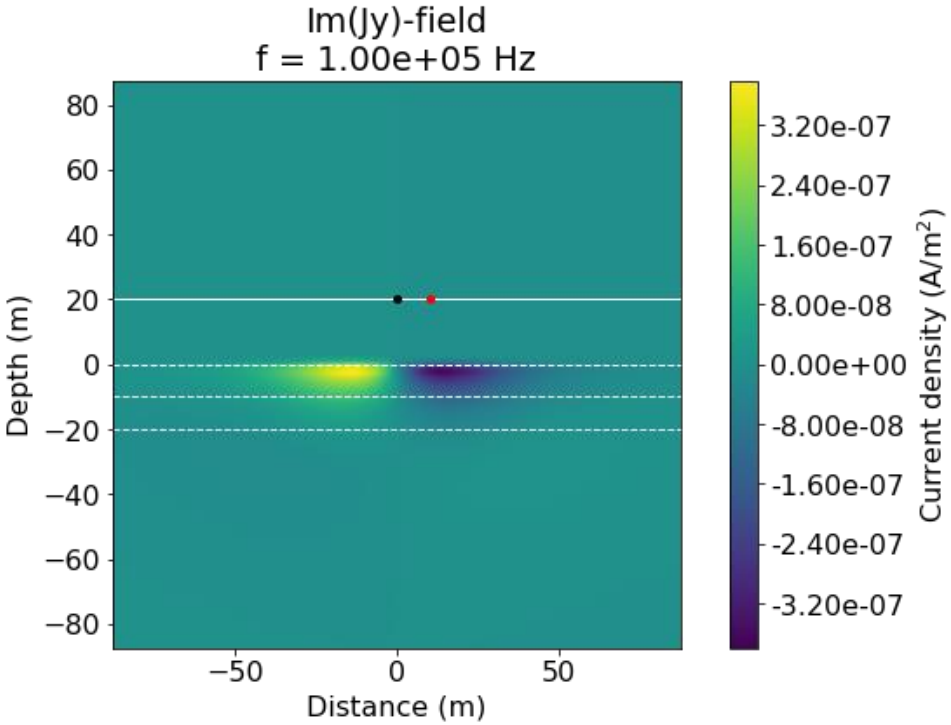


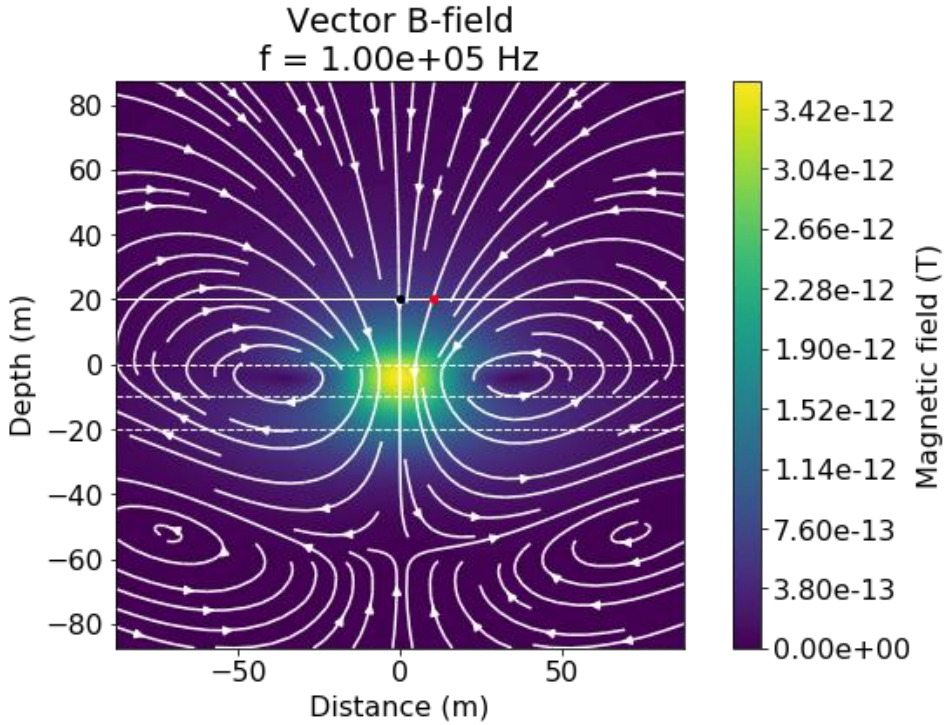


Effects of Frequency

- Frequency at 100 kHz
- Skin depth = 16 m
- Currents are concentrated at surface

$$\delta = 503\sqrt{\frac{\rho}{f}}$$



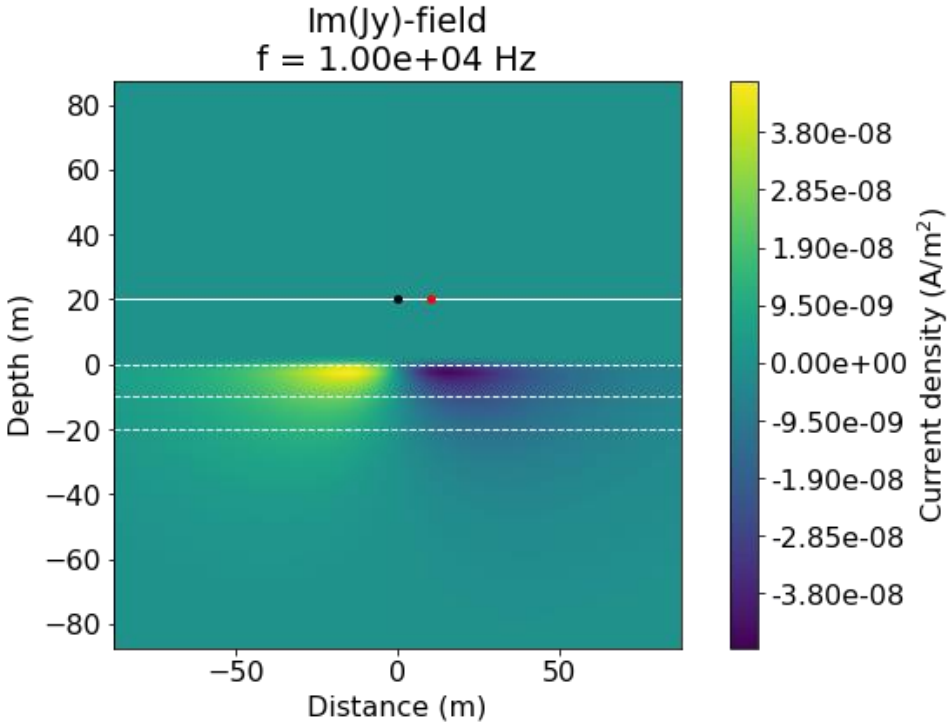


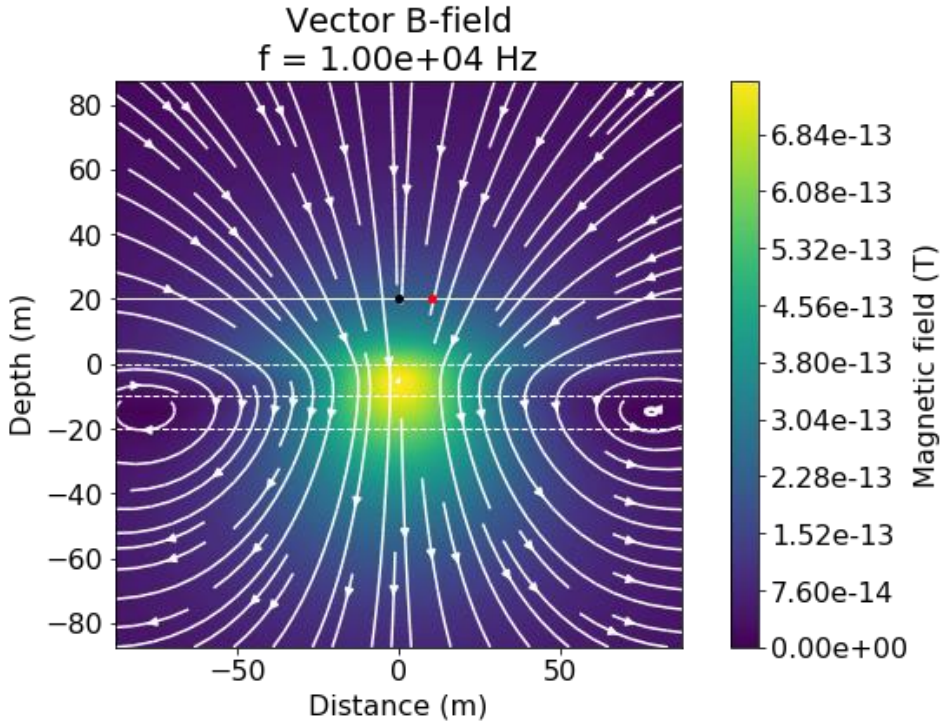
Images created using FDEM_VMD_LayeredEarth.ipynb, 0.01 S/m halfspace, VMD height 20 m.

Effects of Frequency

- Frequency at 10 kHz
- Skin depth = 50 m
- Currents diffusing downward and outward

$$\delta = 503\sqrt{\frac{\rho}{f}}$$





Images created using FDEM_VMD_LayeredEarth.ipynb, 0.01 S/m halfspace, VMD height 20 m.

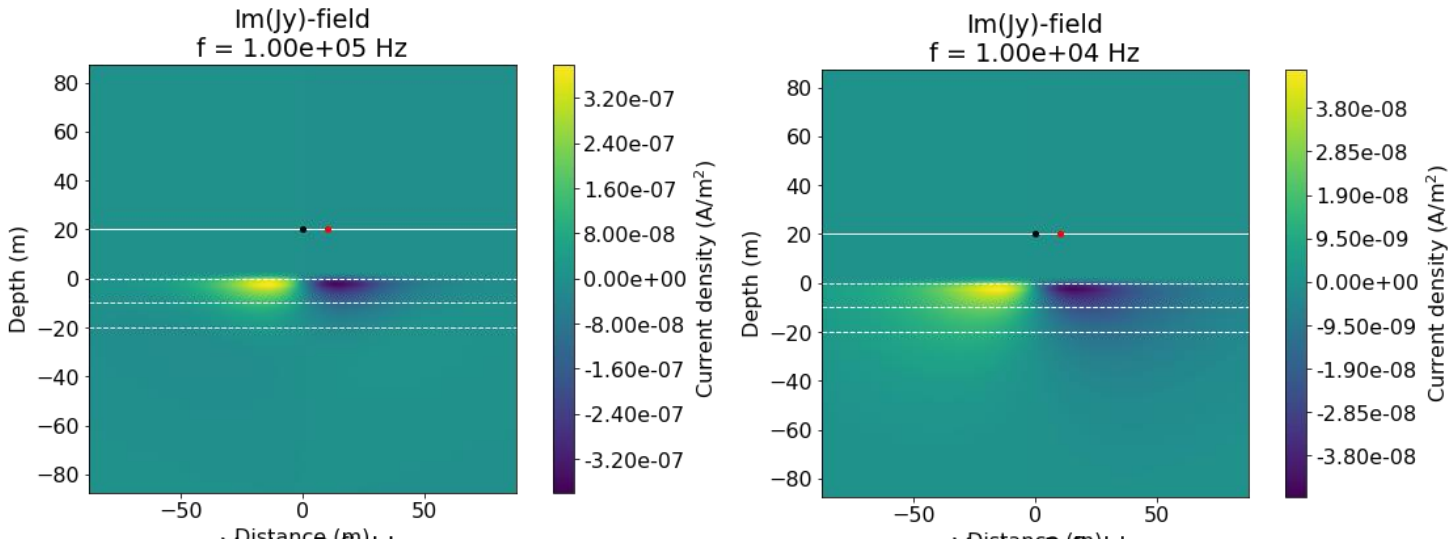
Summary: Effects of Frequency

$$\delta = 503\sqrt{\frac{\rho}{f}}$$

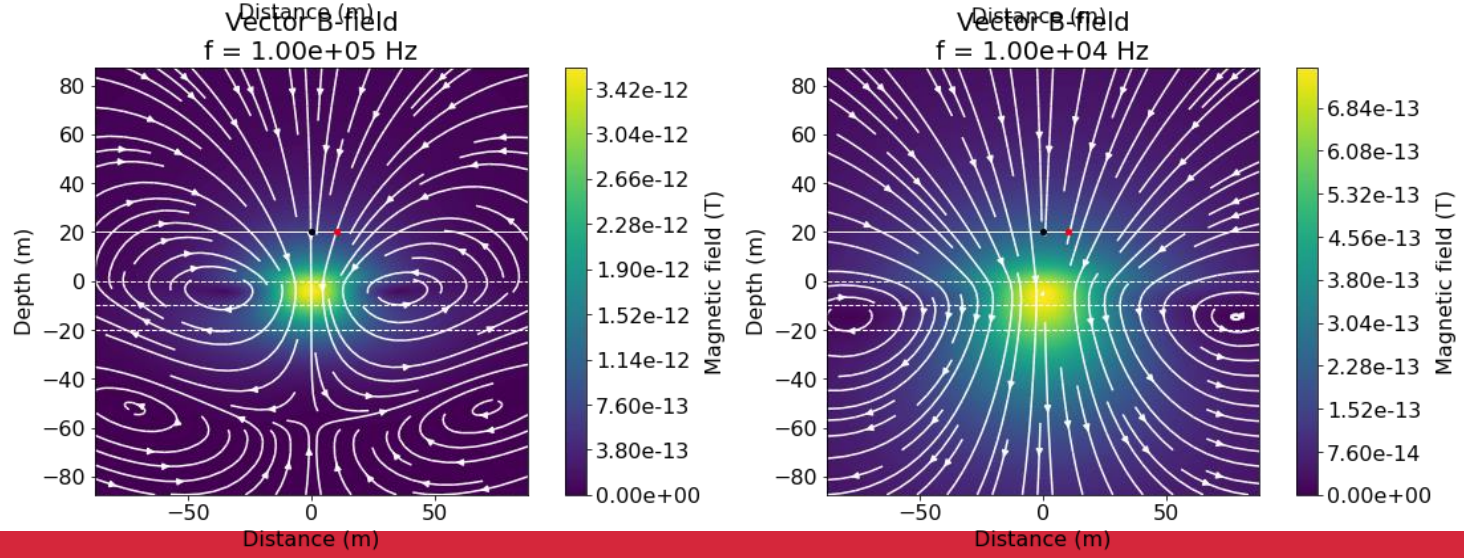
100 kHz

10 kHz

J_y imag.

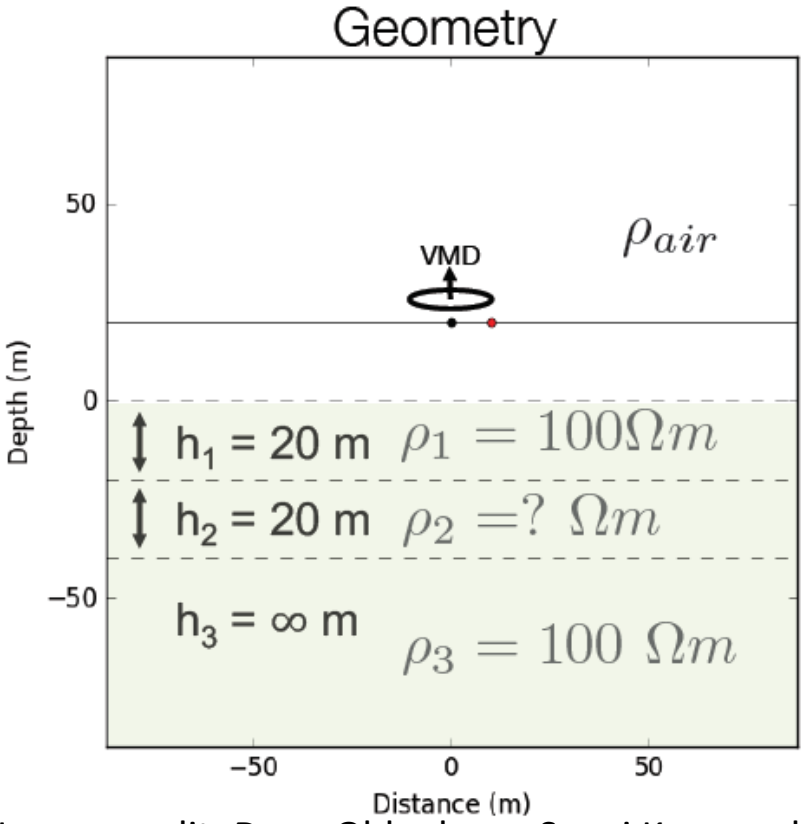


B imag.



Layered earth

- 3 layers + air,
- ρ_2 varies

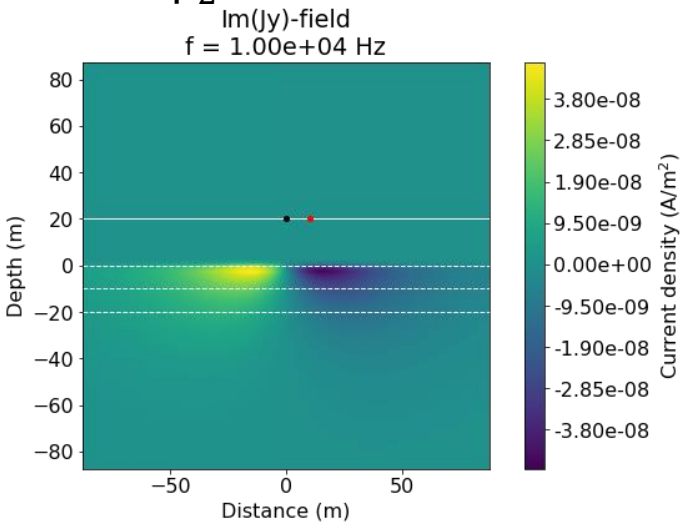


- Four different cases:
  - Halfspace
    ρ_2 = 100 Ωm
  - Resistive
    ρ_2 = 1000 Ωm
  - Conductive
    ρ_2 = 10 Ωm
  - Very conductive
    ρ_2 = 1 Ωm
- Fields
  - J_y imag
  - Secondary **B** imag

Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Current density (J_y imag)

ρ_2 = 100 Ωm



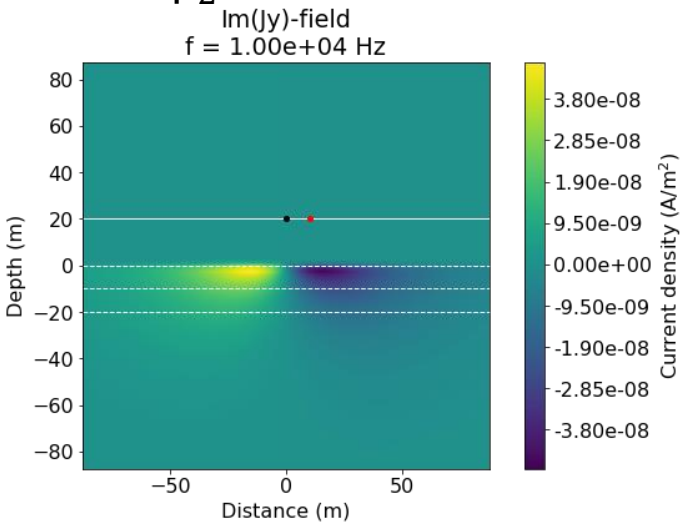
ρ_2 = 1000 Ωm

ρ_2 = 10 Ωm

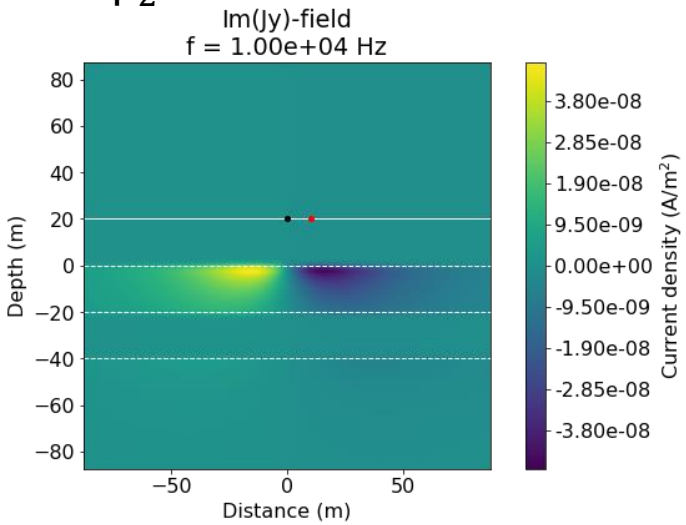
ρ_2 = 1 Ωm

Current density (J_y imag)

ρ_2 = 100 Ωm



ρ_2 = 1000 Ωm

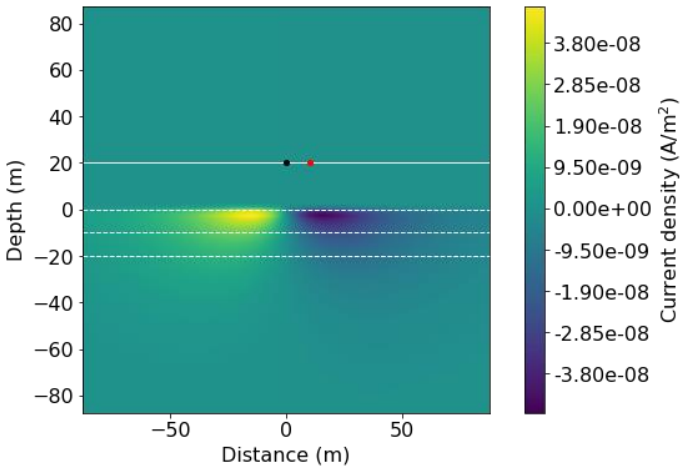


ρ_2 = 10 Ωm

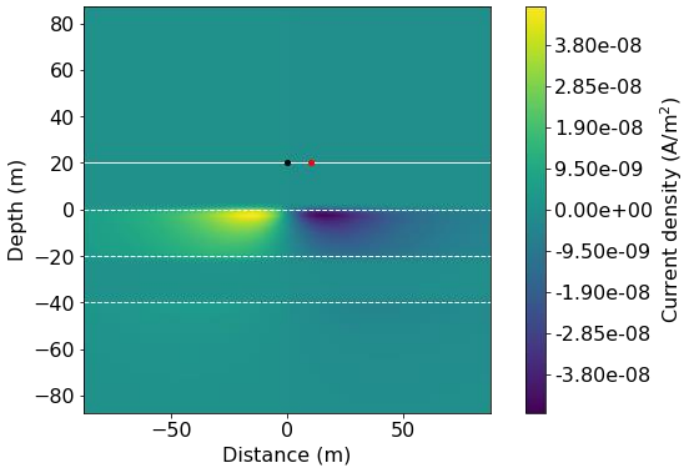
ρ_2 = 1 Ωm

Current density (J_y imag)

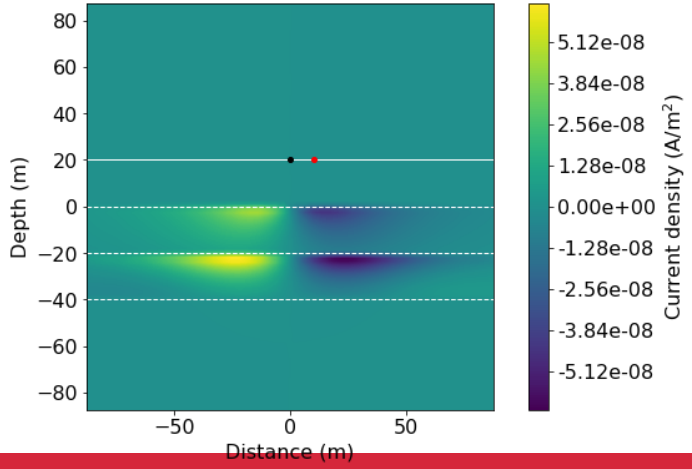
ρ_2 = 100 Ωm



ρ_2 = 1000 Ωm



ρ_2 = 10 Ωm

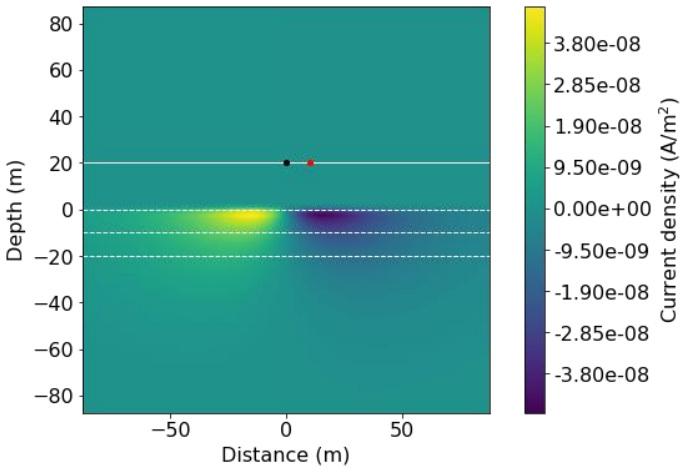


ρ_2 = 1 Ωm

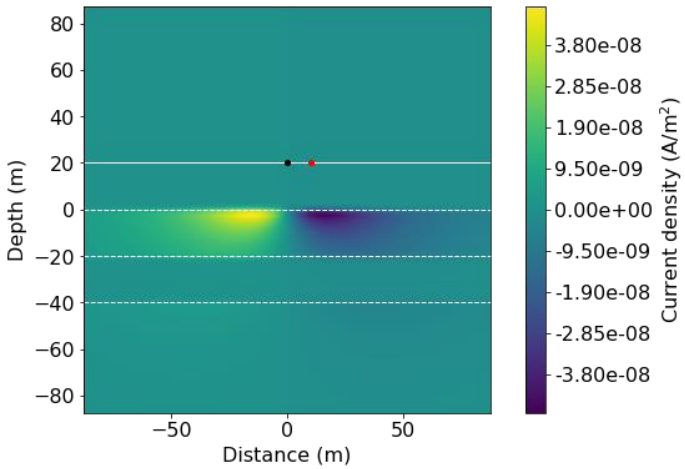
Current density (J_y imag)

Images created using FDEM_VMD_LayeredEarth.ipynb, 0.01 S/m halfspace, VMD height 20 m.

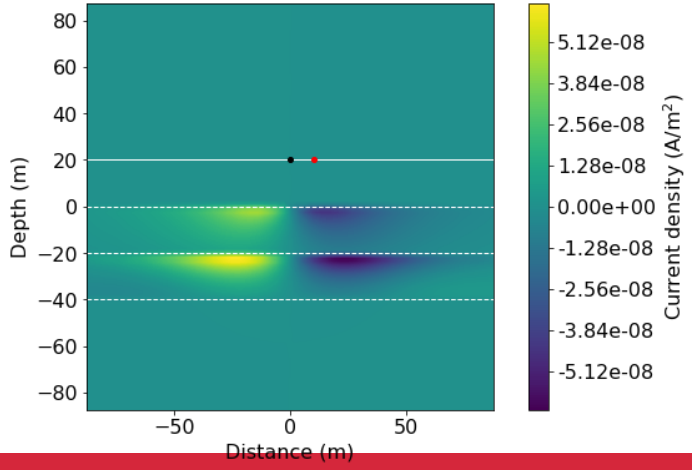
ρ_2 = 100 Ωm



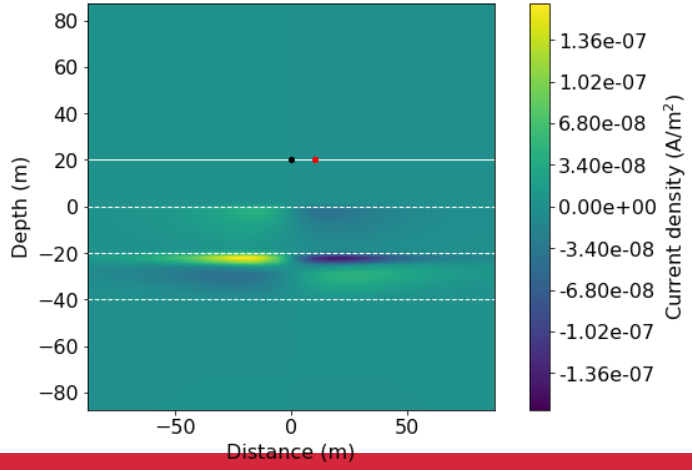
ρ_2 = 1000 Ωm



ρ_2 = 10 Ωm

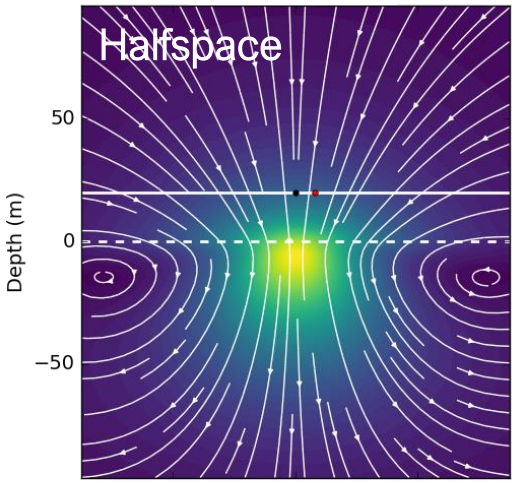


ρ_2 = 1 Ωm

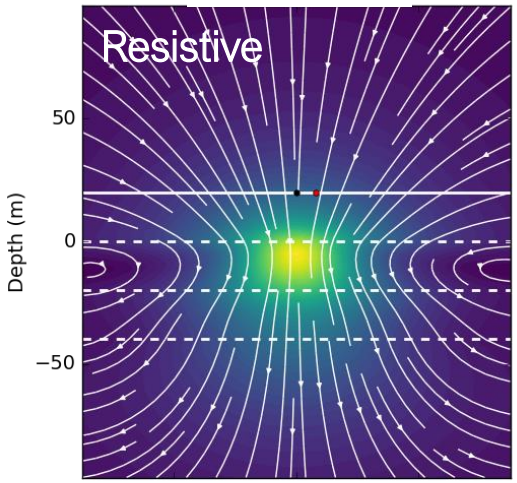


Magnetic flux density (**Bz** imag)

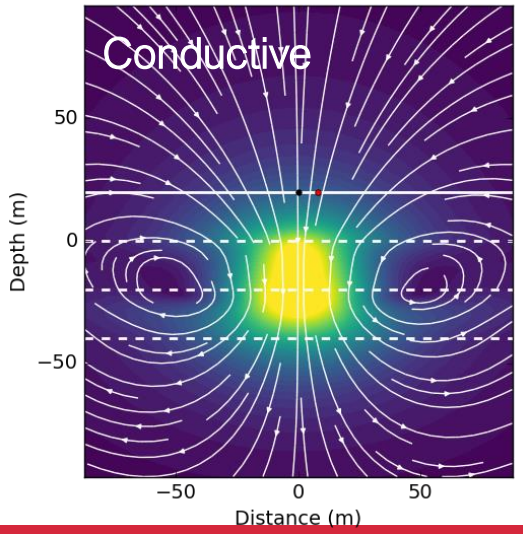
ρ_2 = 100 Ωm



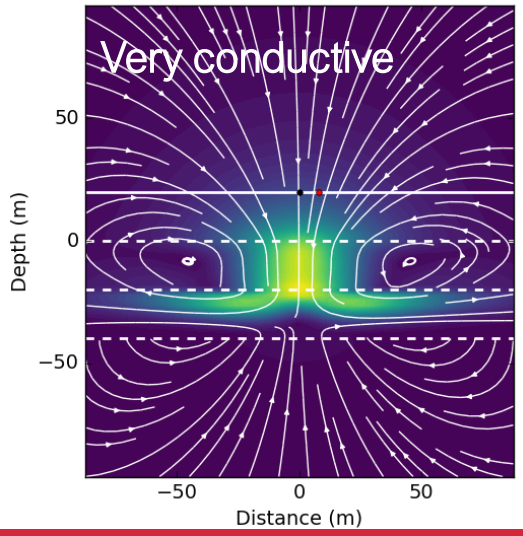
ρ_2 = 1000 Ωm



ρ_2 = 10 Ωm



ρ_2 = 1 Ωm



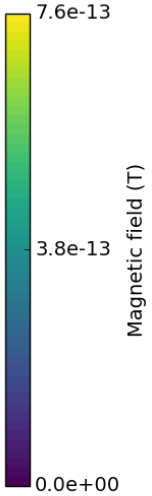
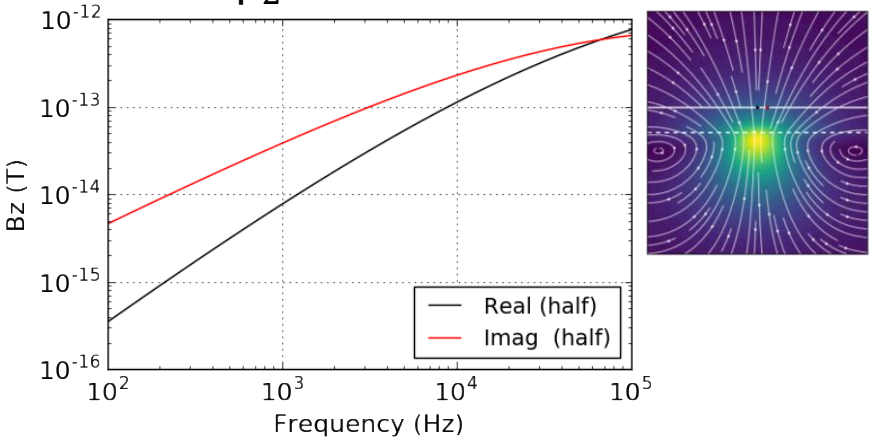


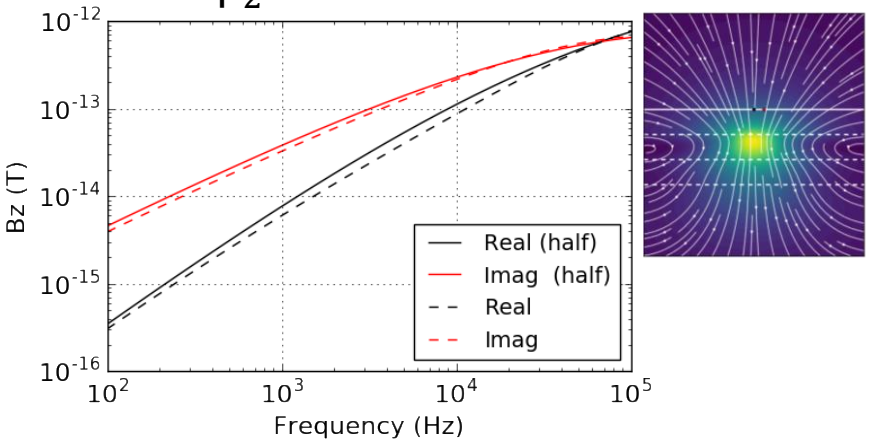
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

B_z sounding curves

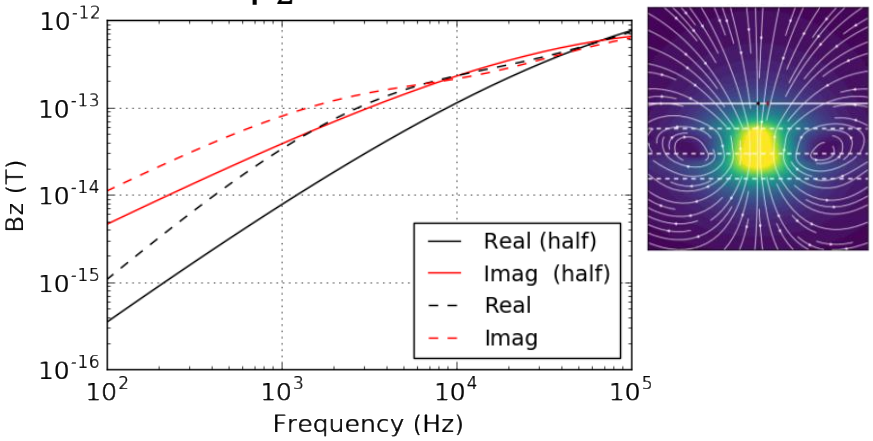
ρ_2 = 100 Ωm



ρ_2 = 1000 Ωm



ρ_2 = 10 Ωm



ρ_2 = 1 Ωm

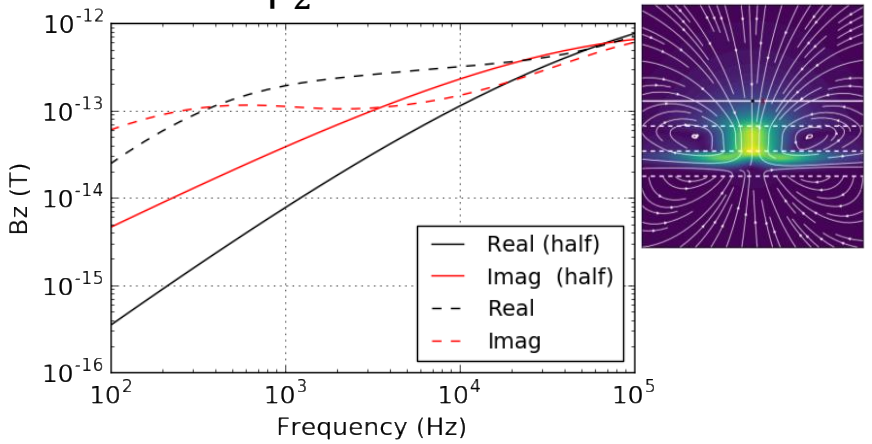


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

“shielding” problem

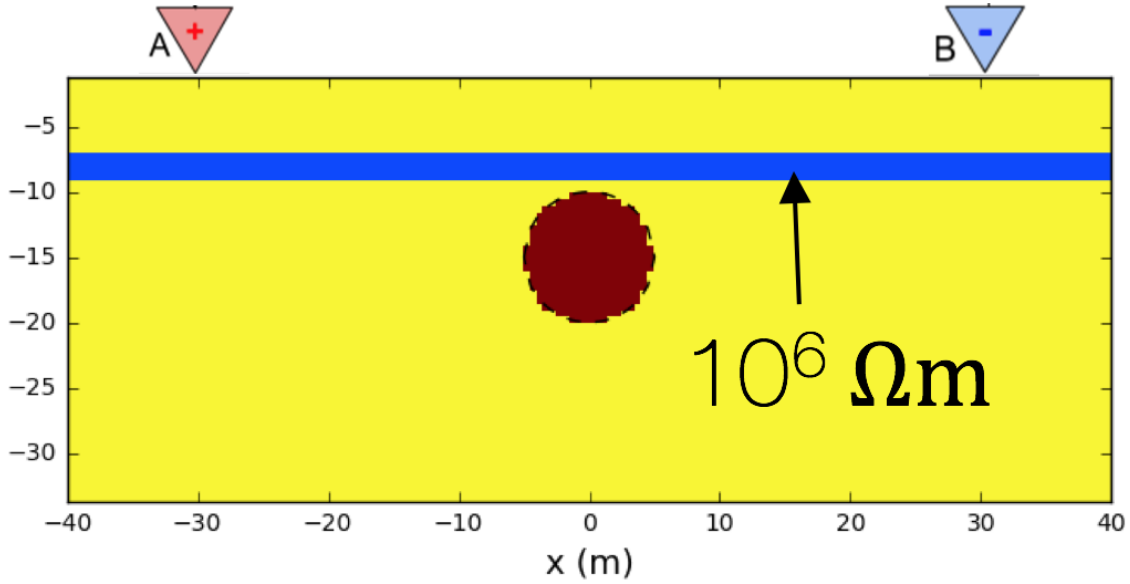
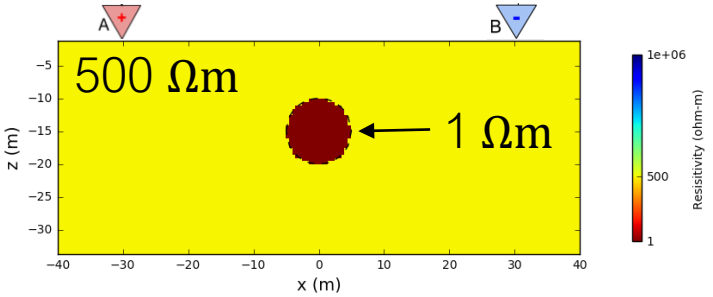


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

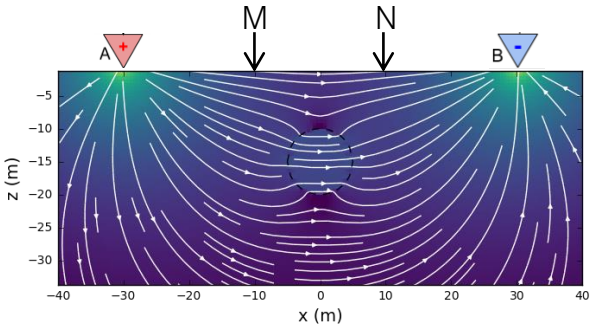
Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)



Currents and measured data at MN

ρ_a = 430 Ωm



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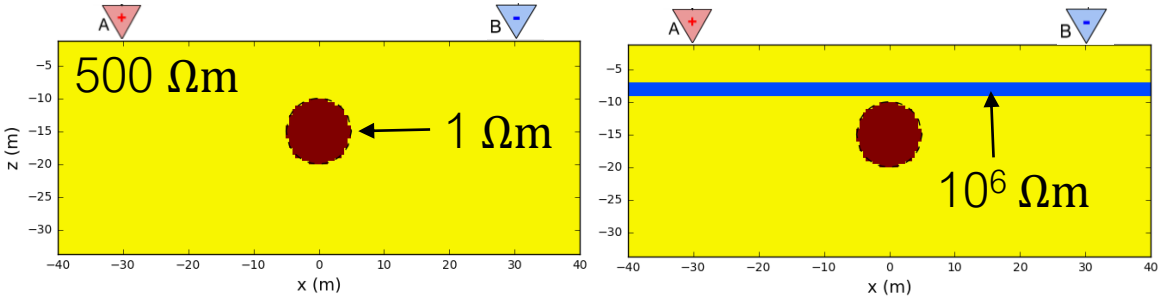
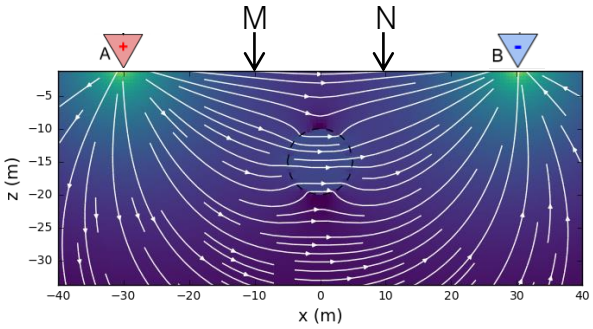
Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)



Currents and measured data at MN

ρ_a = 430 Ωm



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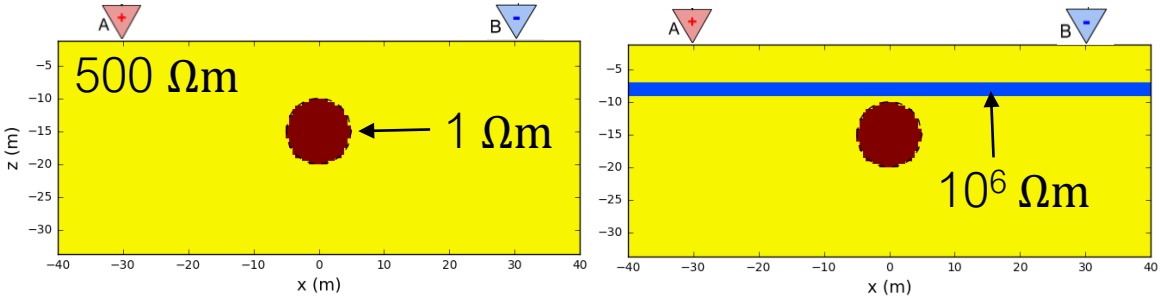
Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)



Currents and measured data at MN

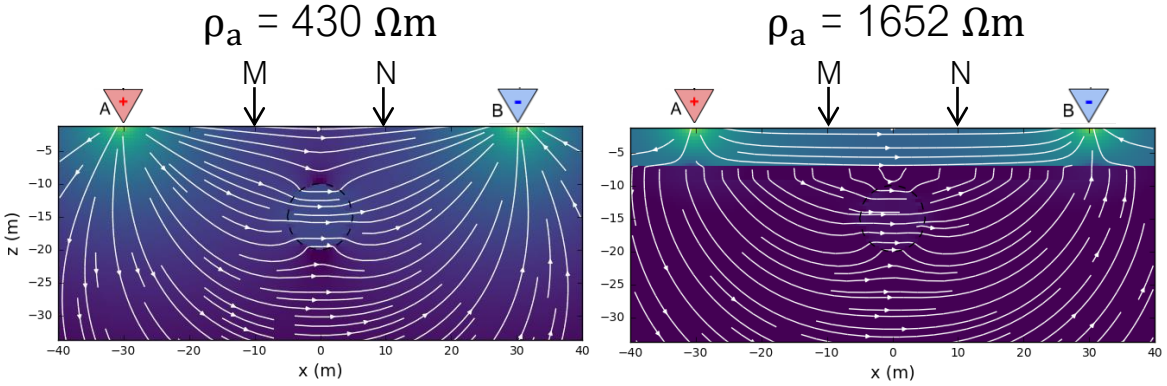
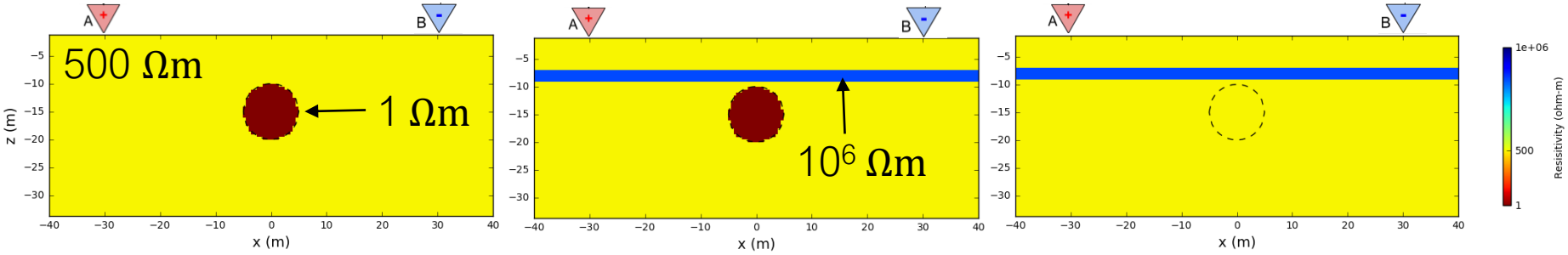


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)



Currents and measured data at MN

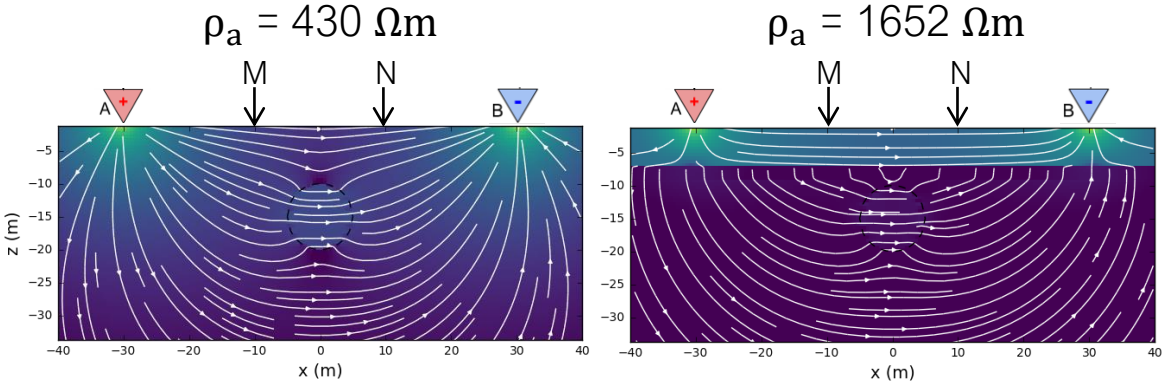
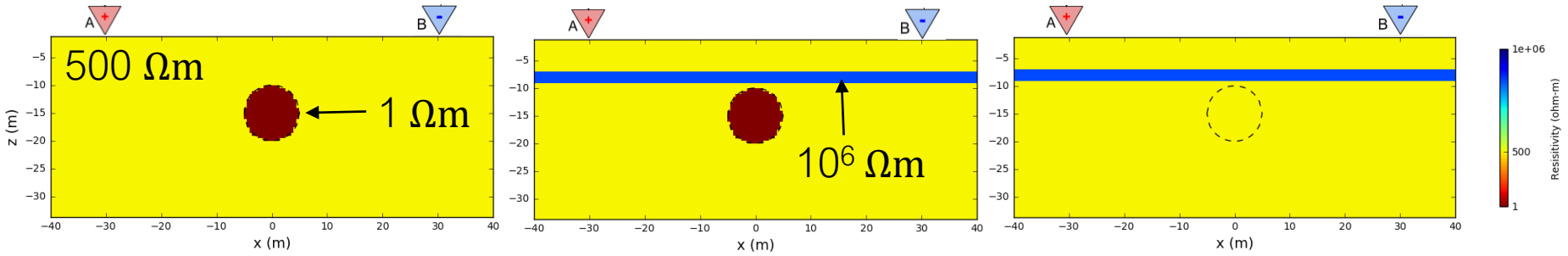


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Shielding: DC with resistive layer

Resistivity models (thin **resistive** layer)



Currents and measured data at MN

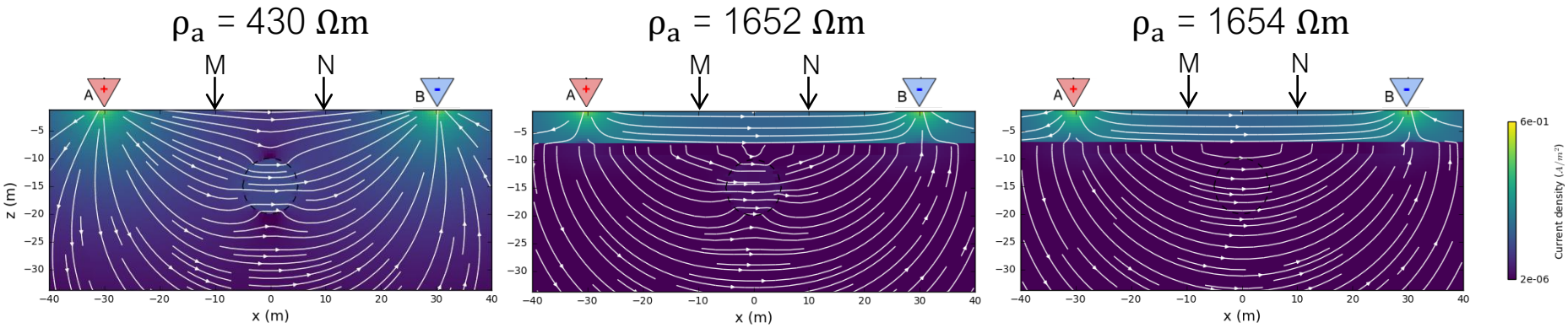
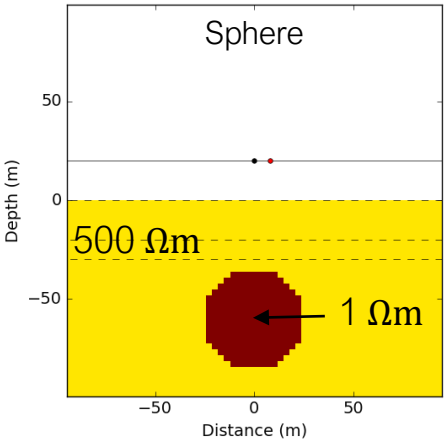


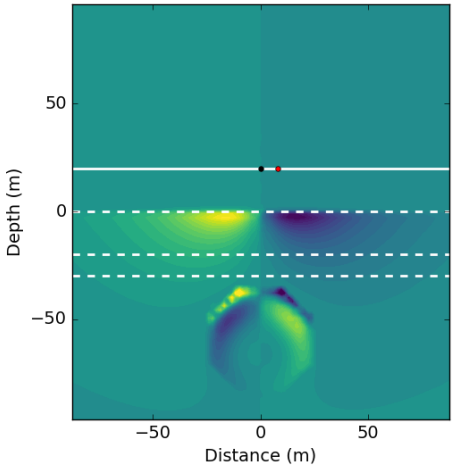
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

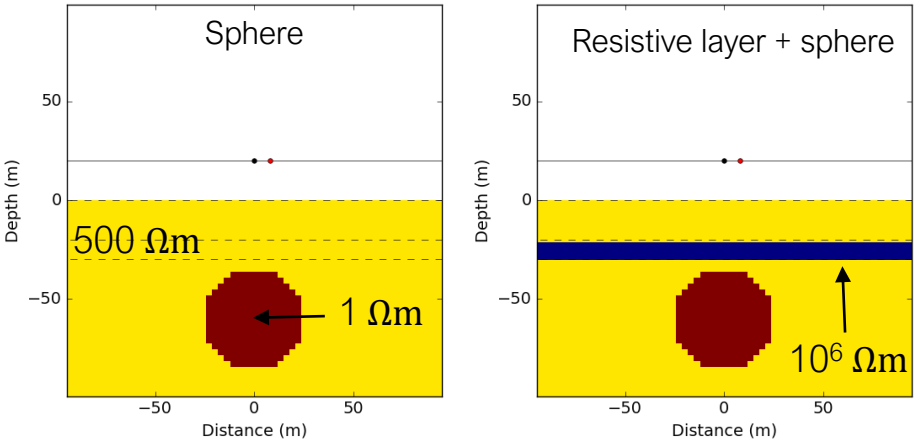


Currents (J_y imag)

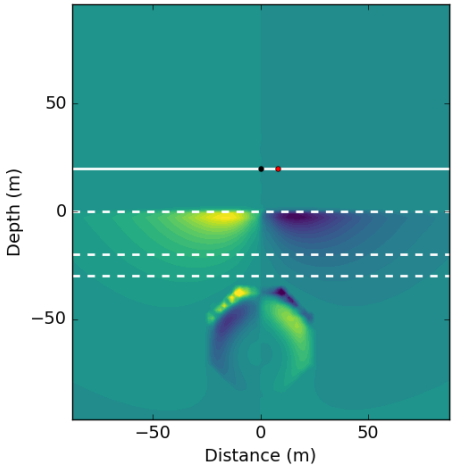


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

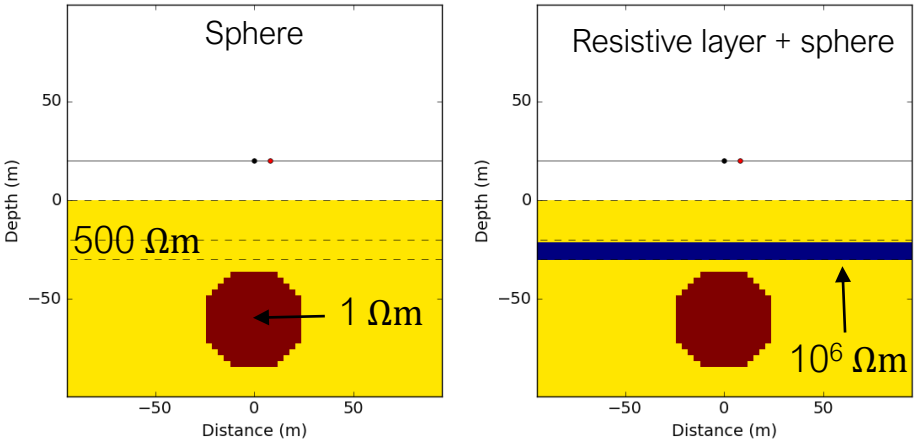


Currents (J_y imag)

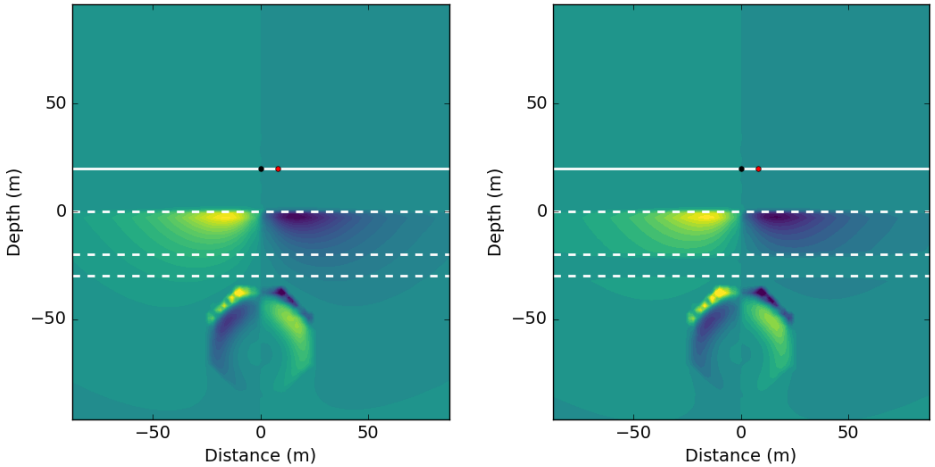


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

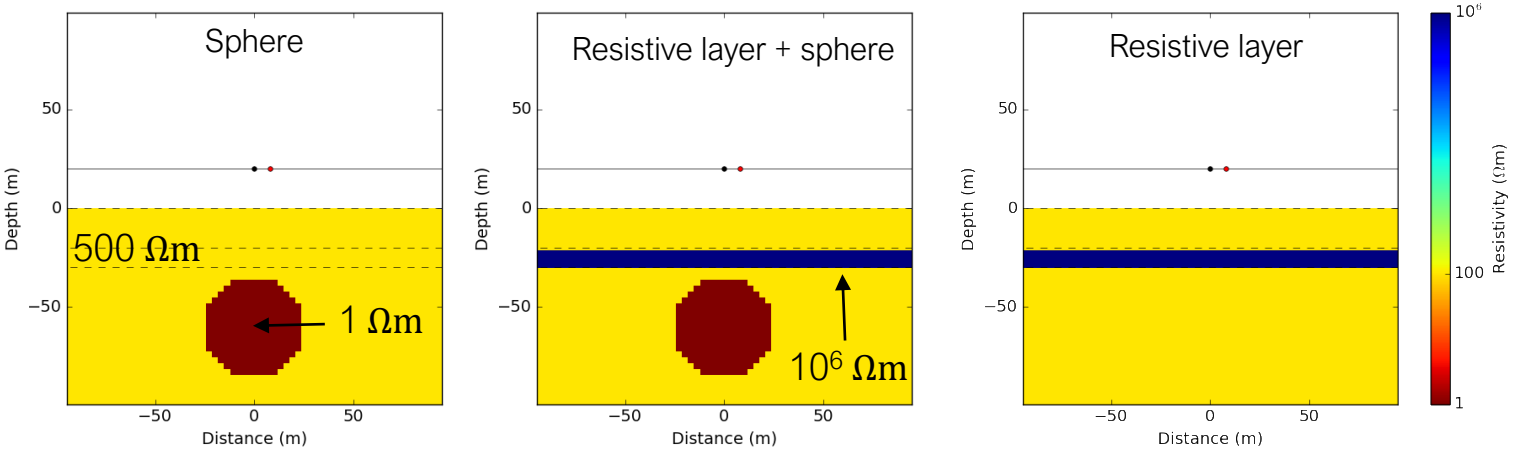


Currents (J_y imag)

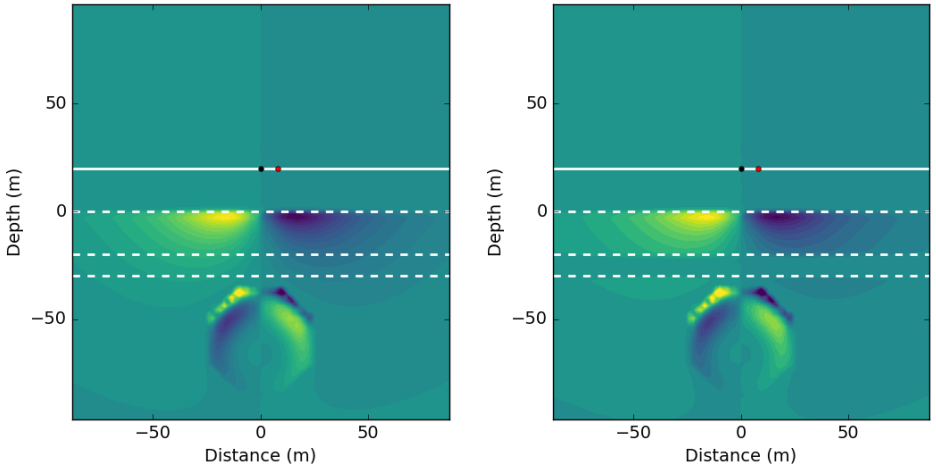


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

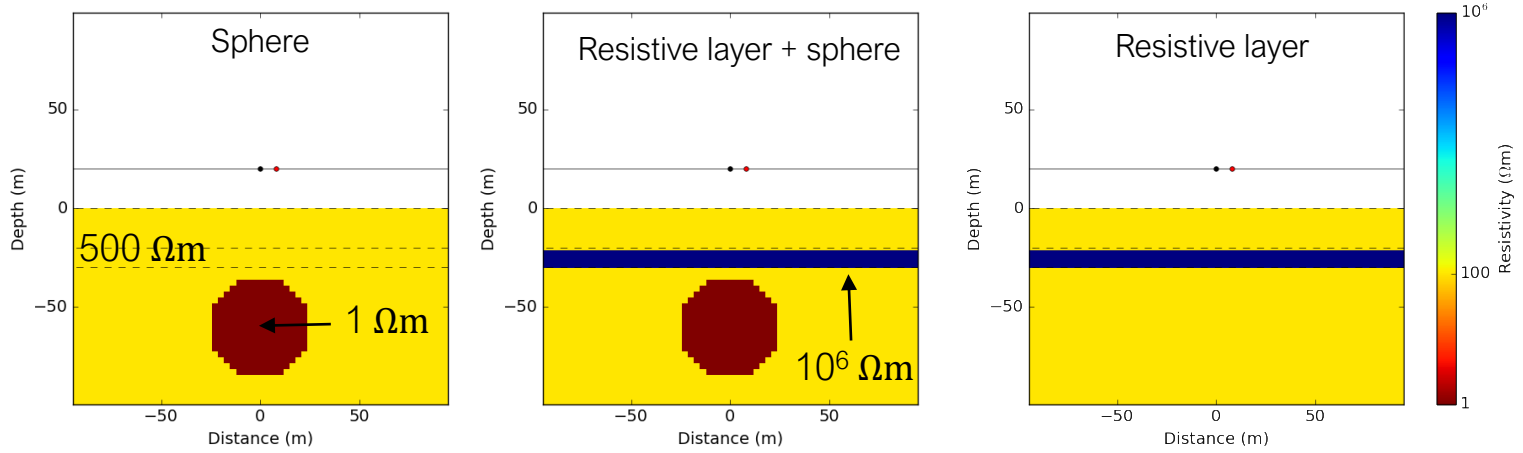


Currents (J_y imag)

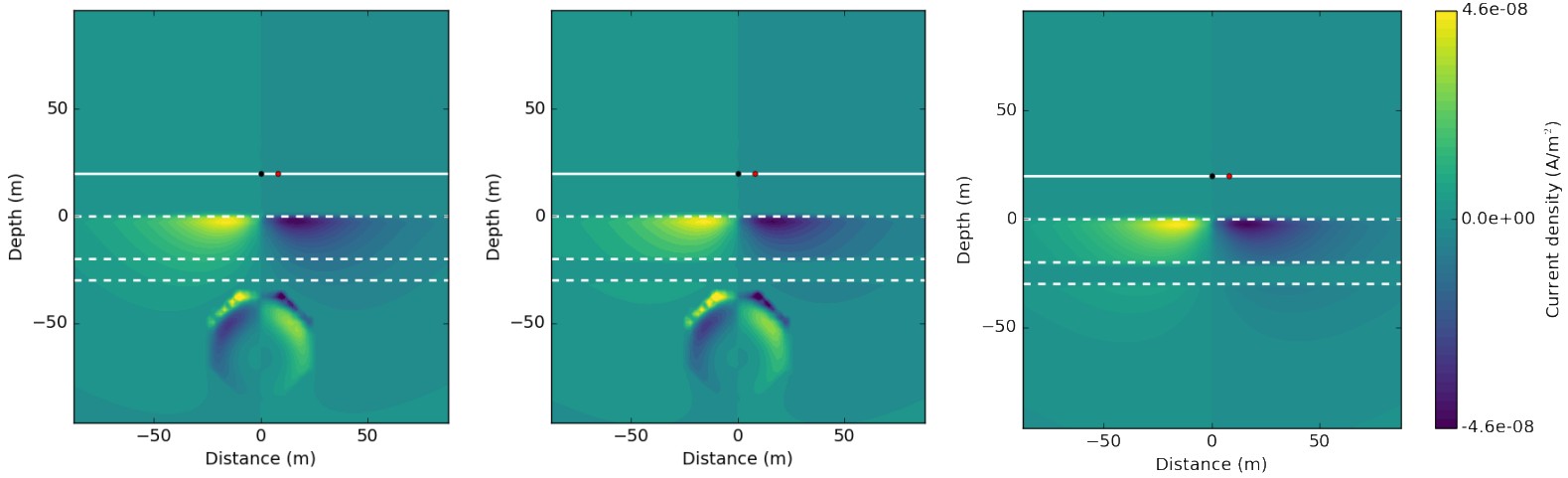


Shielding: EM with resistive layer

Resistivity models (thin **resistive** layer)

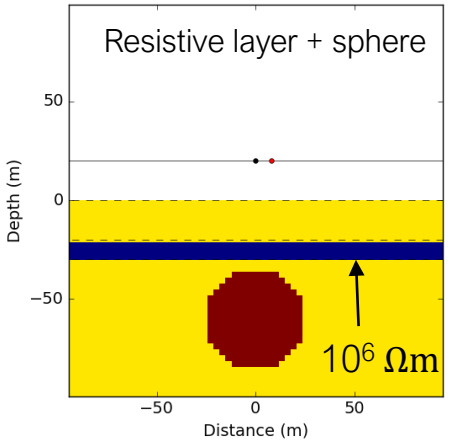


Currents (J_y imag)

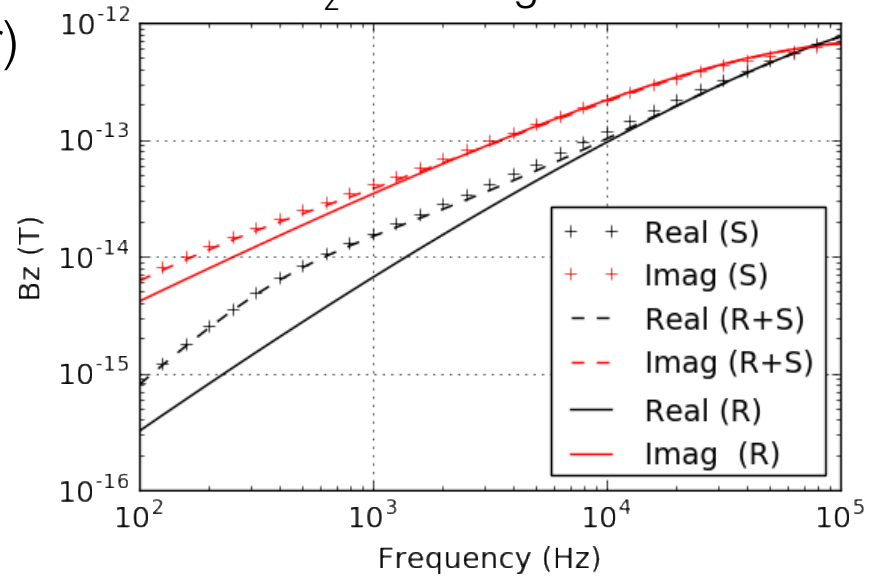


Shielding: EM with resistive layer

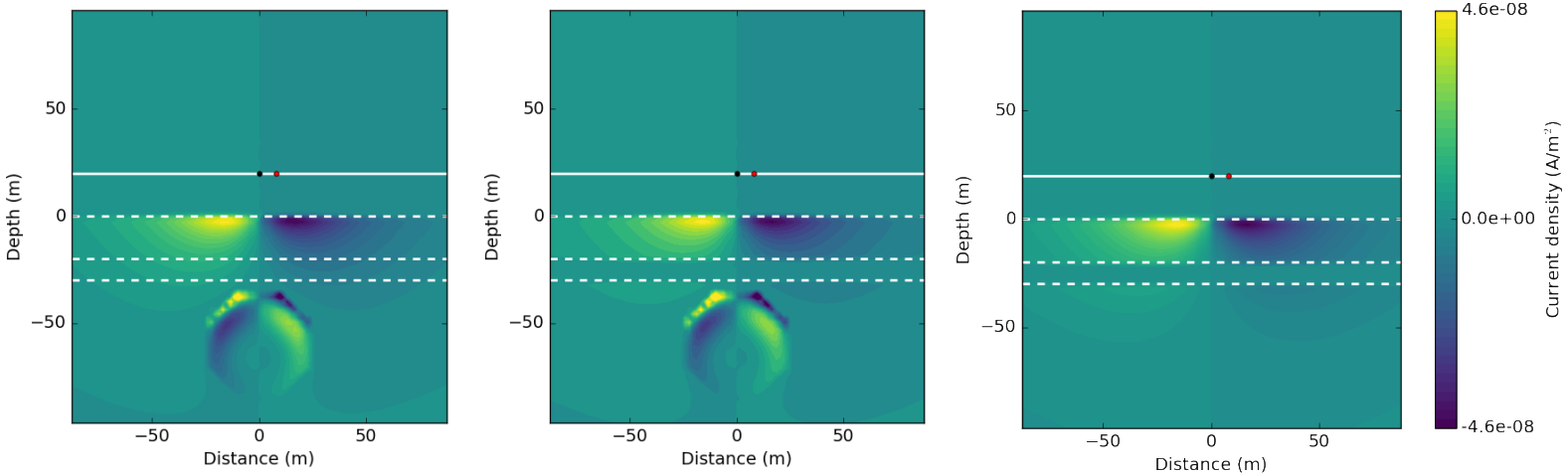
Resistivity models (thin **resistive** layer)



B_z sounding curves

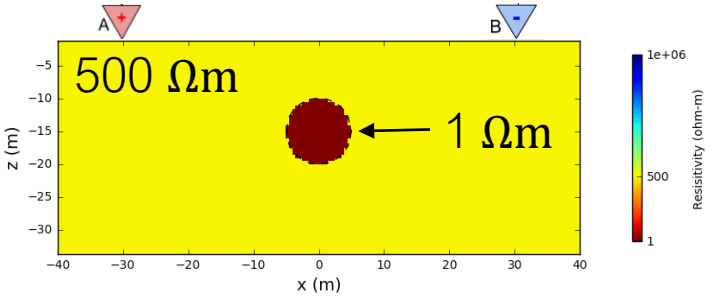


Currents (J_y imag)



Shielding: DC with conductive layer

Resistivity models (thin **conductive** layer)



Currents and measured data at MN

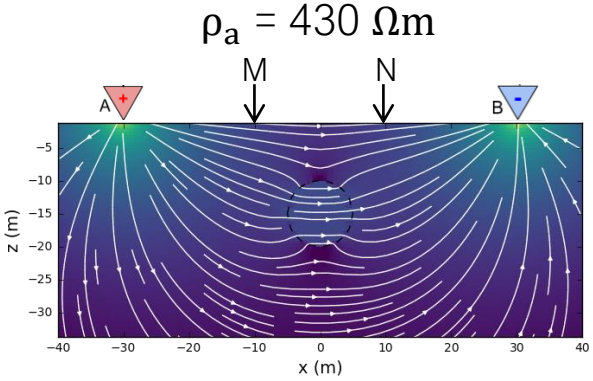
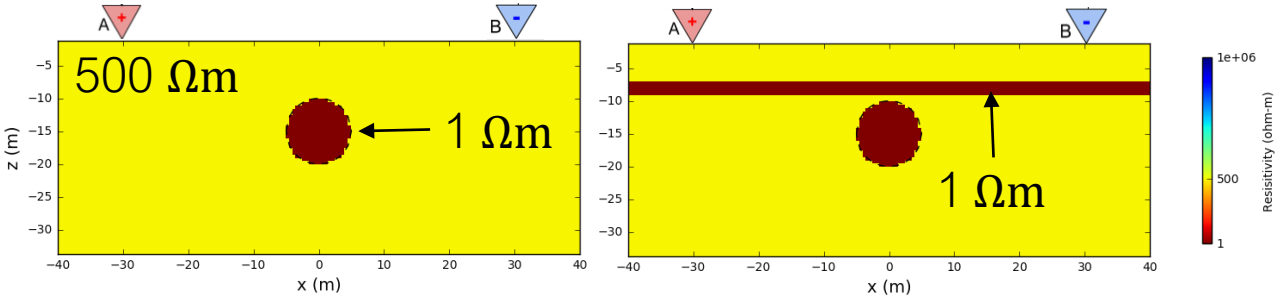


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Shielding: DC with conductive layer

Resistivity models (thin **conductive** layer)



Currents and measured data at MN

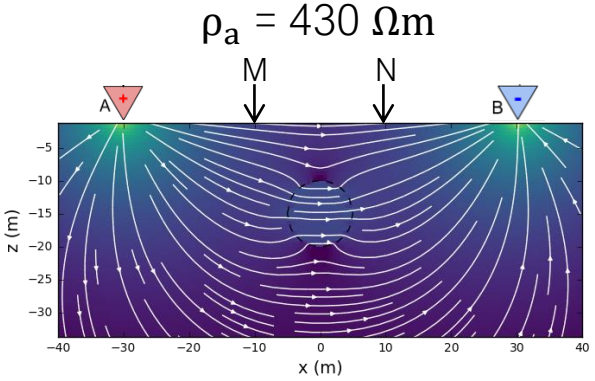
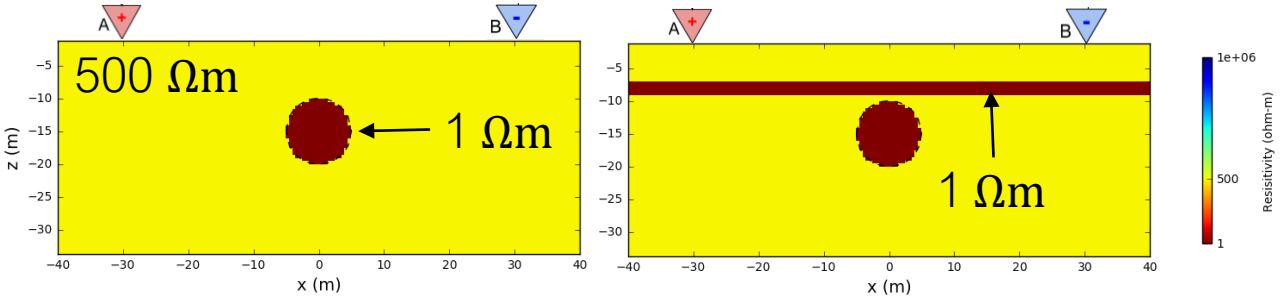


Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Shielding: DC with conductive layer

Resistivity models (thin **conductive** layer)



Currents and measured data at MN

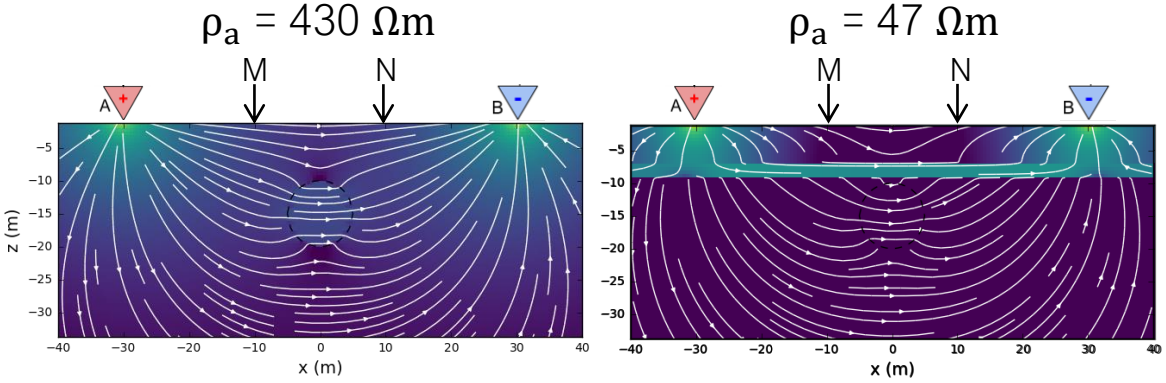
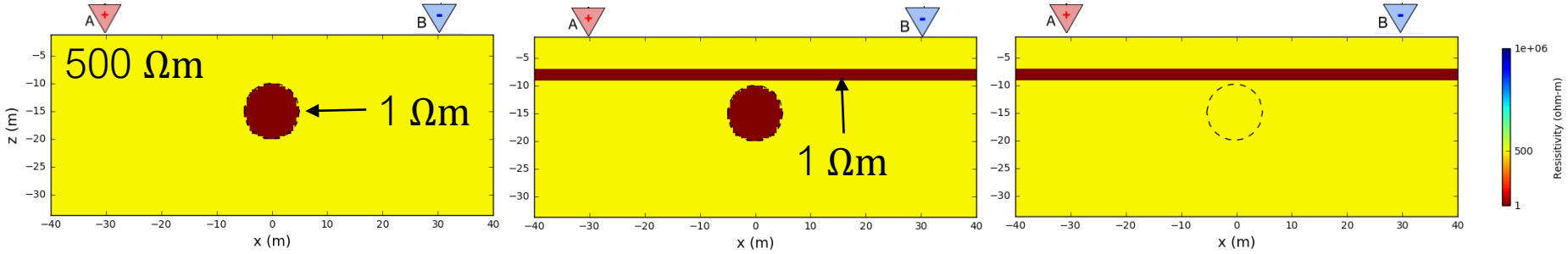


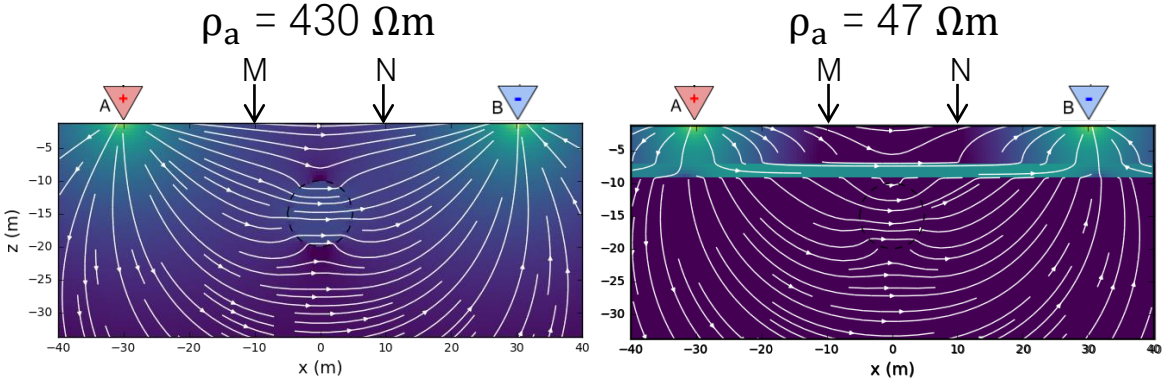
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Shielding: DC with conductive layer

Resistivity models (thin **conductive** layer)



Currents and measured data at MN



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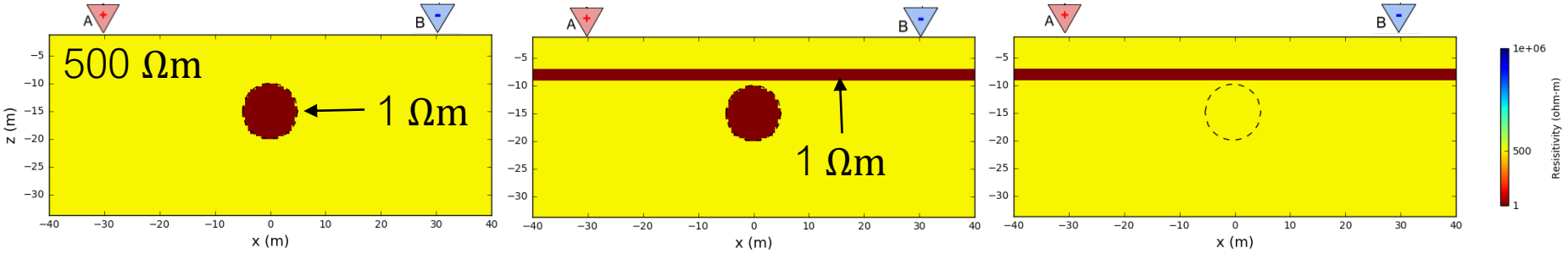
Shielding: DC with conductive layer

Resistivity models (thin **conductive** layer)



Currents and measured data at MN

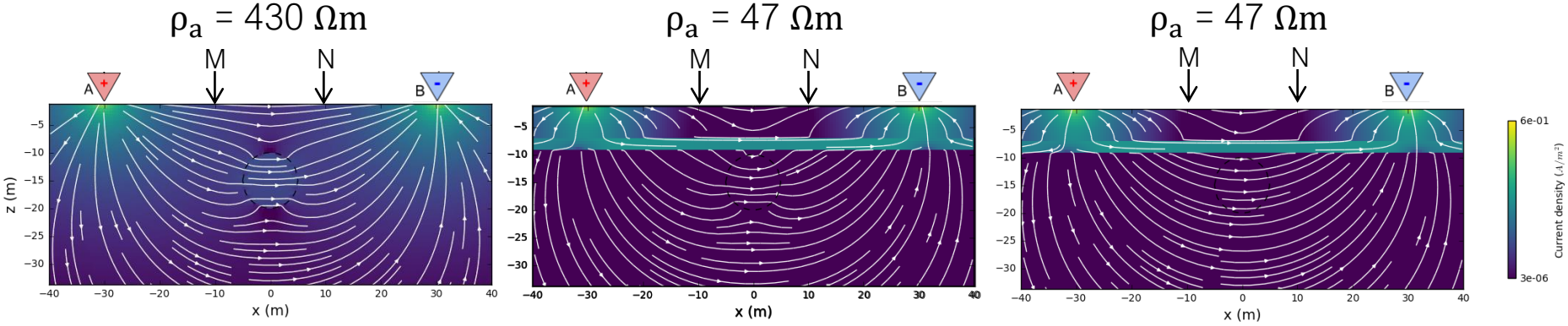
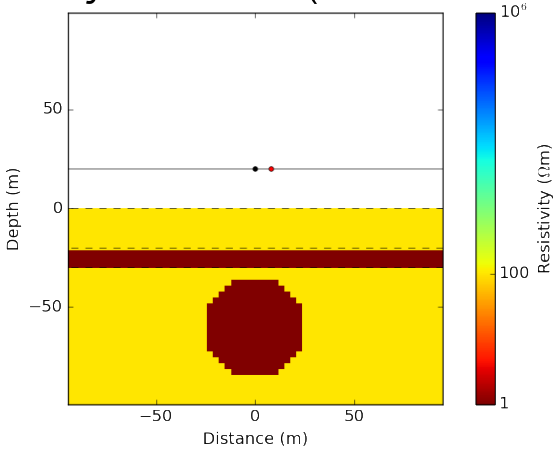


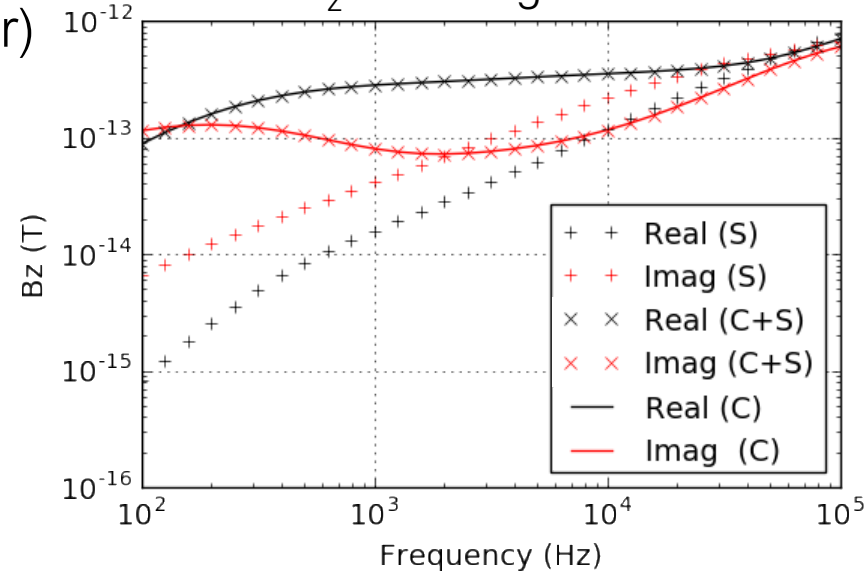
Image credit: Doug Oldenburg, Seogi Kang and Linsey Heagy from UBC-GIF

Shielding: EM with conductive layer

Resistivity models (thin **conductive** layer)

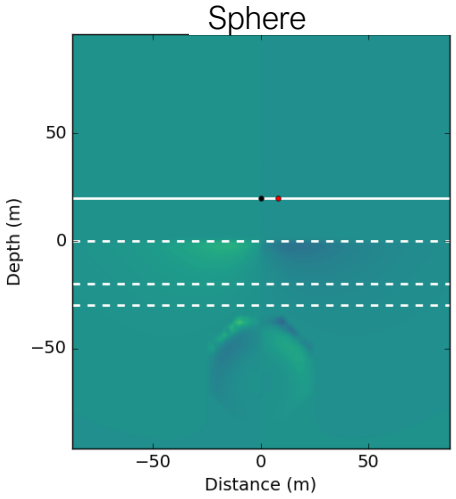


B_z sounding curves



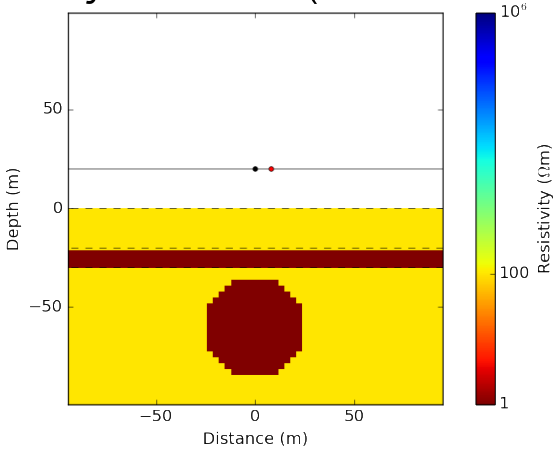
Currents (J_y imag)

Sphere

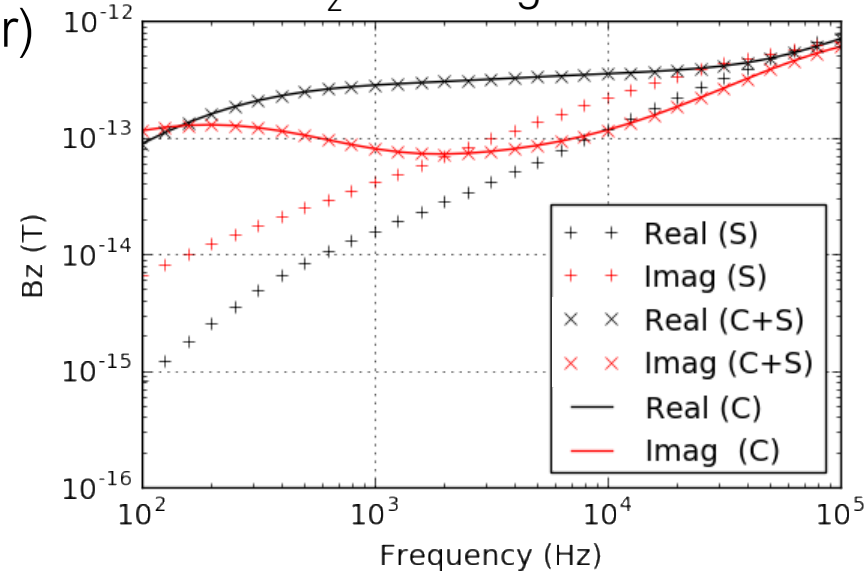


Shielding: EM with conductive layer

Resistivity models (thin **conductive** layer)



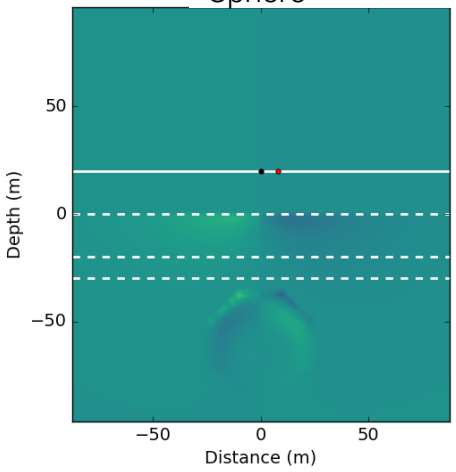
B_z sounding curves



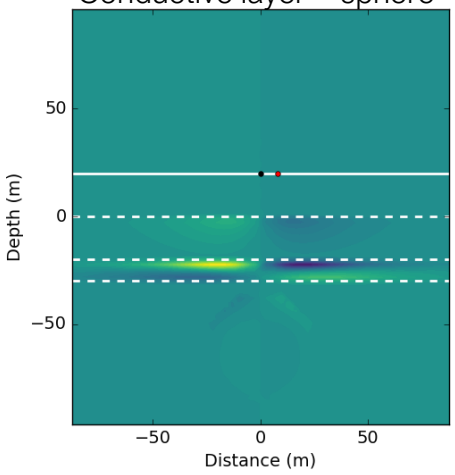
Conductive layer

Currents (J_y imag)

Sphere

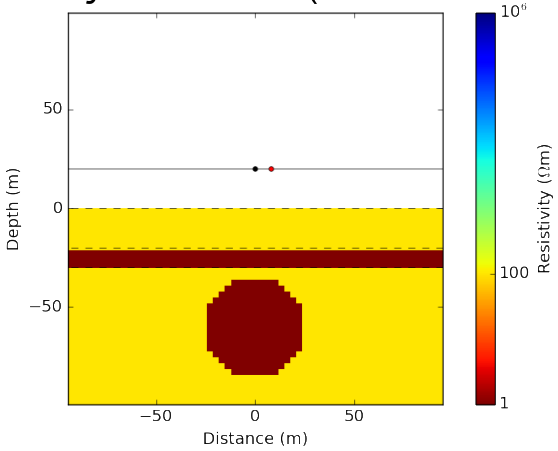


Conductive layer + sphere

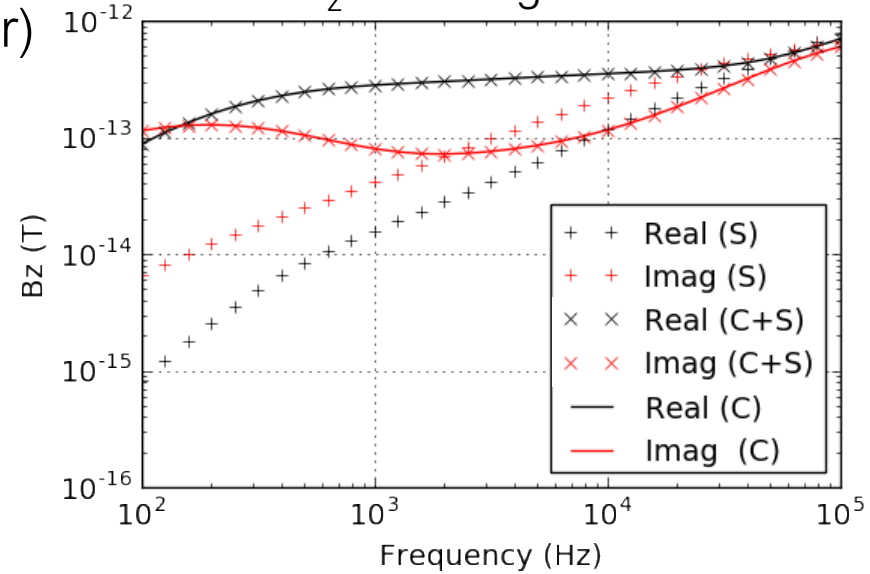


Shielding: EM with conductive layer

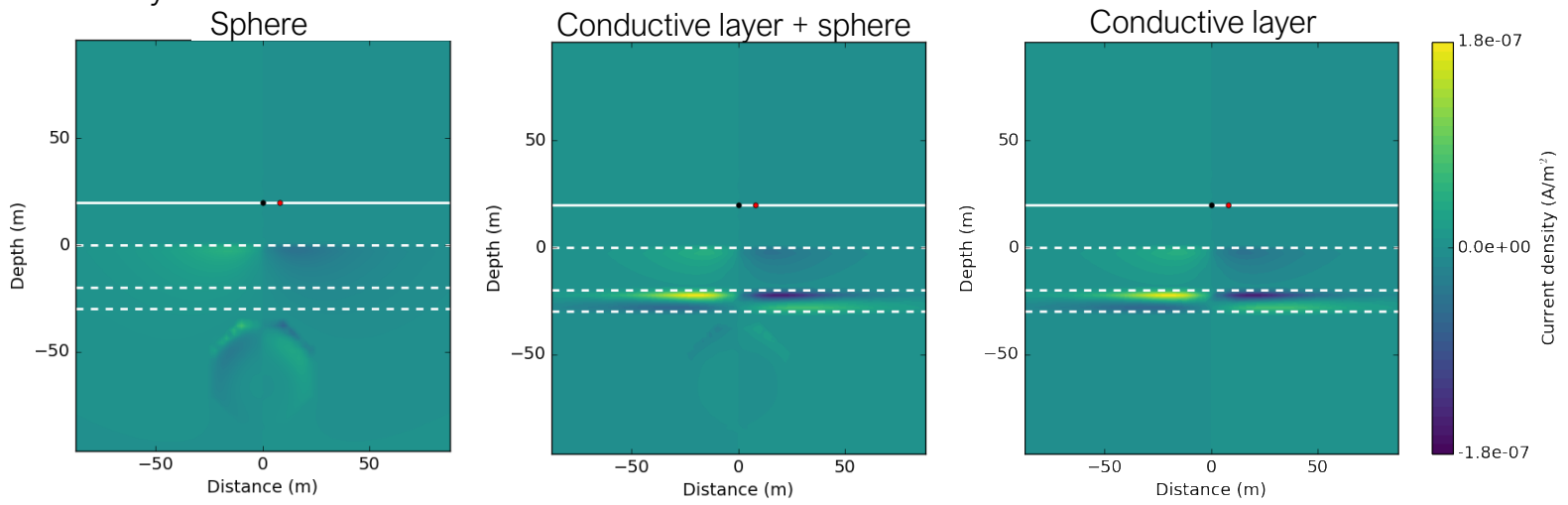
Resistivity models (thin **conductive** layer)



B_z sounding curves



Currents (J_y imag)



Case History: Bookpurnong

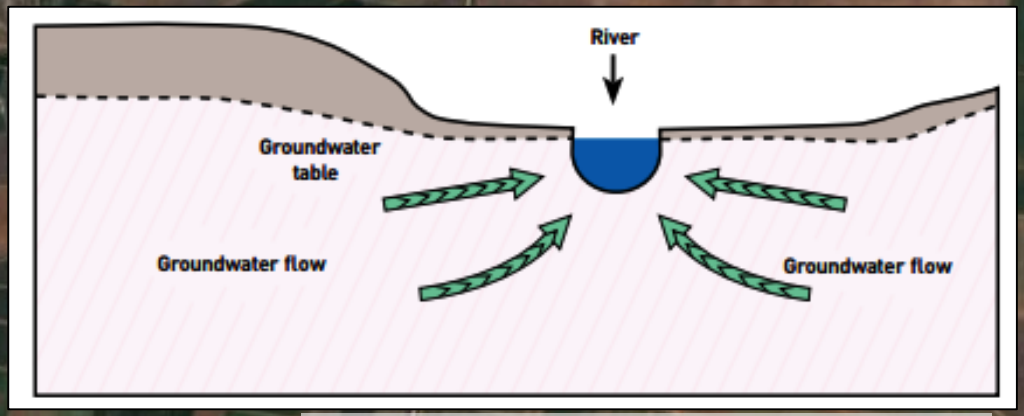
Viezzoli et al., 2009

Setup

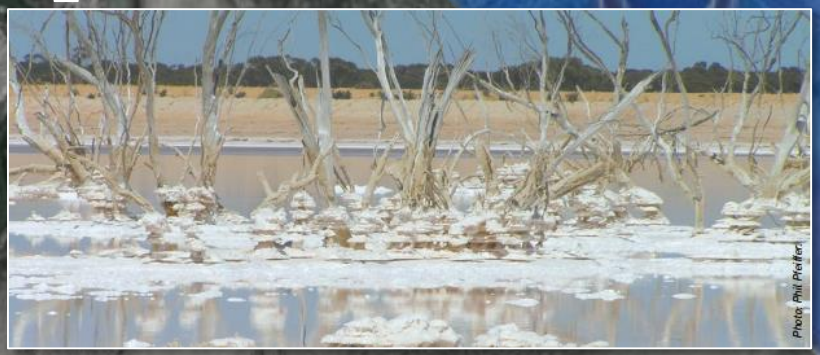
Bookpurnong Irrigation Area

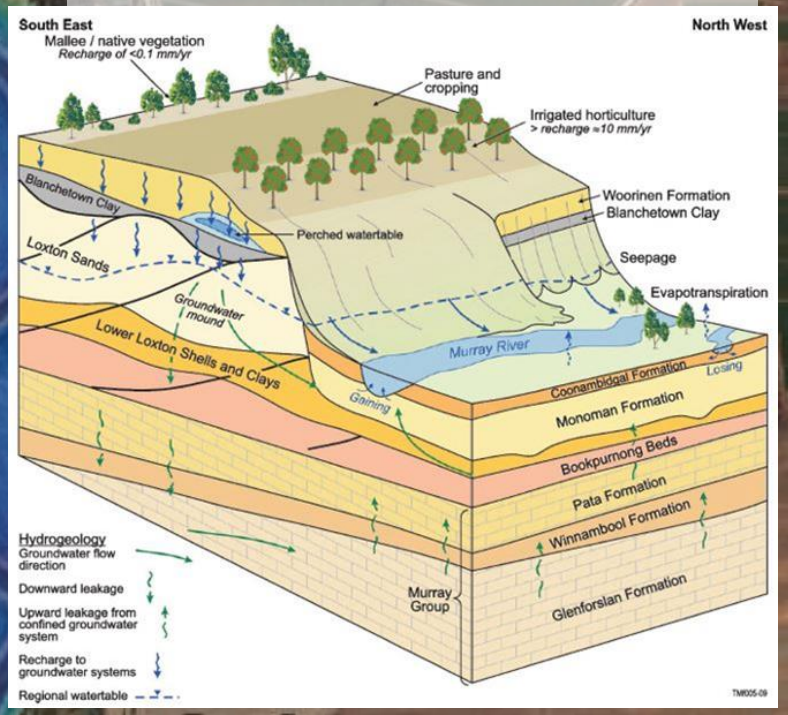
Murray River Floodplain

1 km

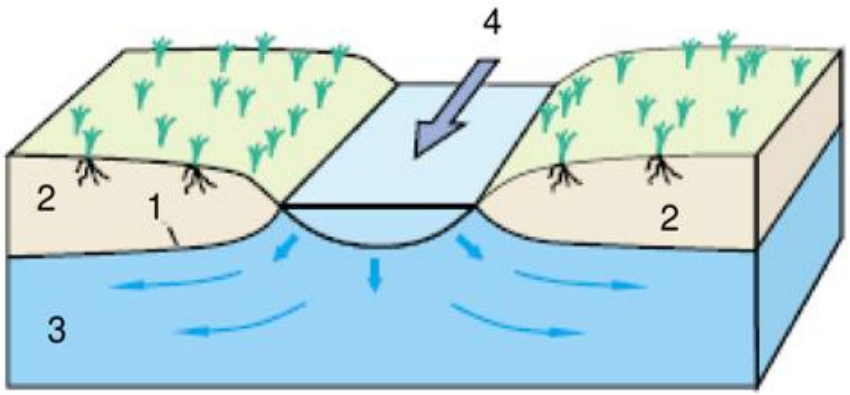


- over-irrigation and drought
- saline water recharges river
- floodplain salinization
- ecological damage

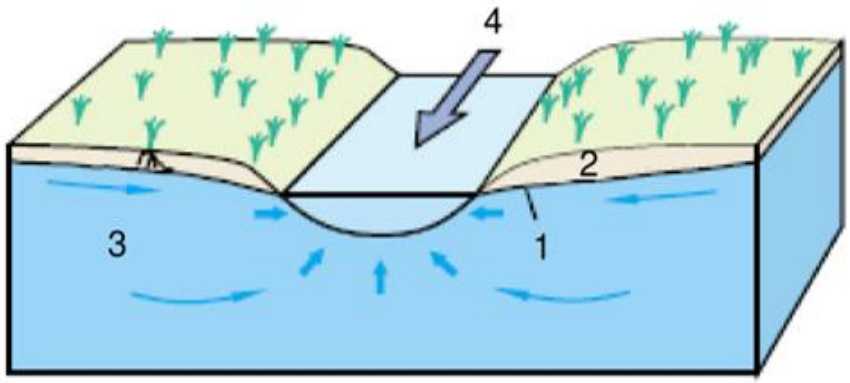




Losing Stream



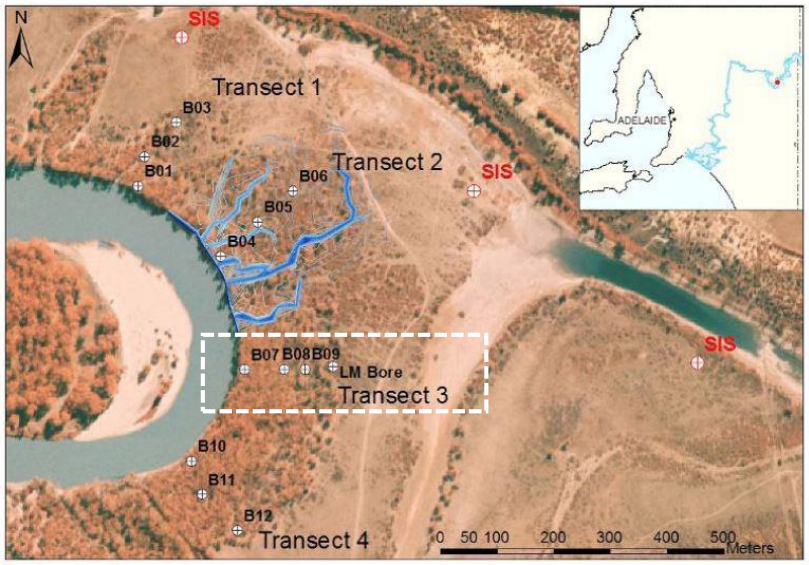
Gaining Stream



1 – Water table 2 – Unsaturated zone 3 – Saturated zone 4 – Flow direction

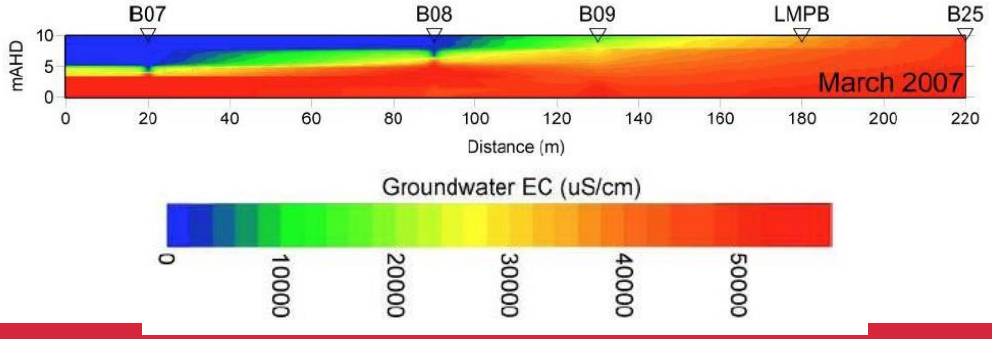
Properties

Location map for salinity measurements



Unit	Conductivity
Saline water	High, 3 - 5 S/m
Fresh water	Low, 0.01 S/m

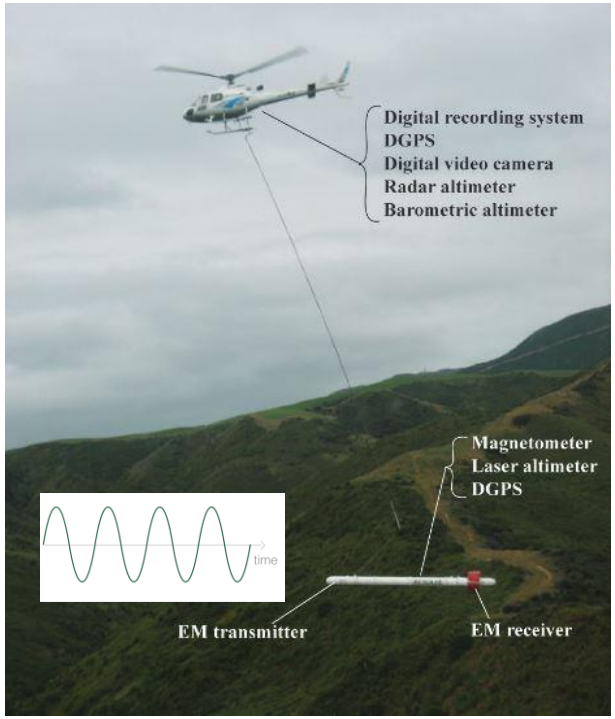
Conductivity from salinity measurements



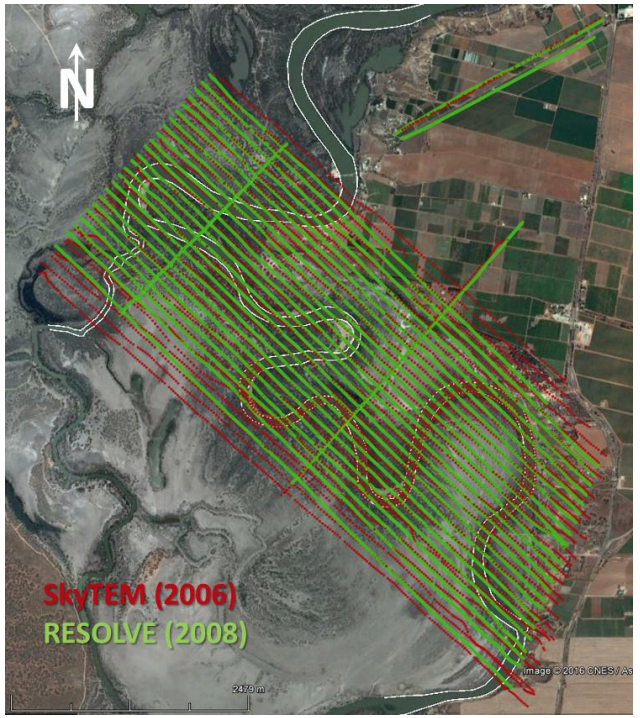
Holland et. al., 2008.

Survey

Resolve system (2008)



Flight lines



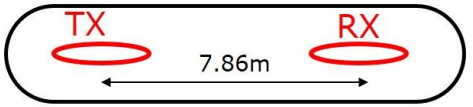
Horizontal Co-planar (HCP) frequencies:

- 382, 1822, 7970, 35920 and 130100 Hz

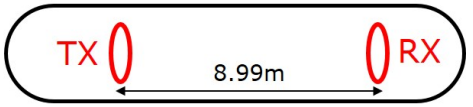
Vertical Co-axial (VCA) frequencies:

- 3258 Hz

Horizontal Co-planar



Vertical Co-axial

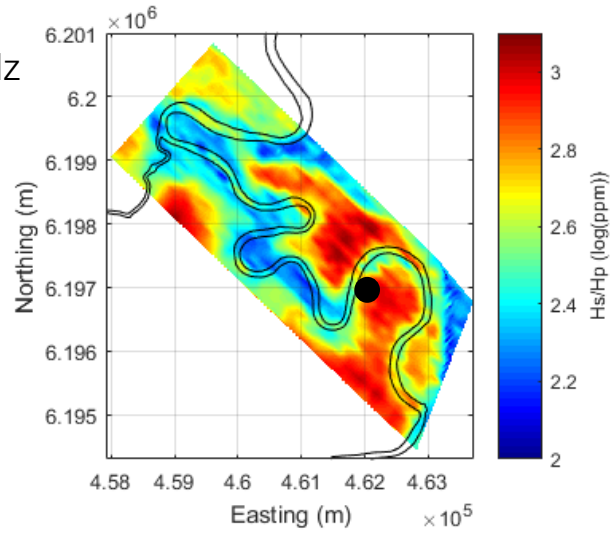


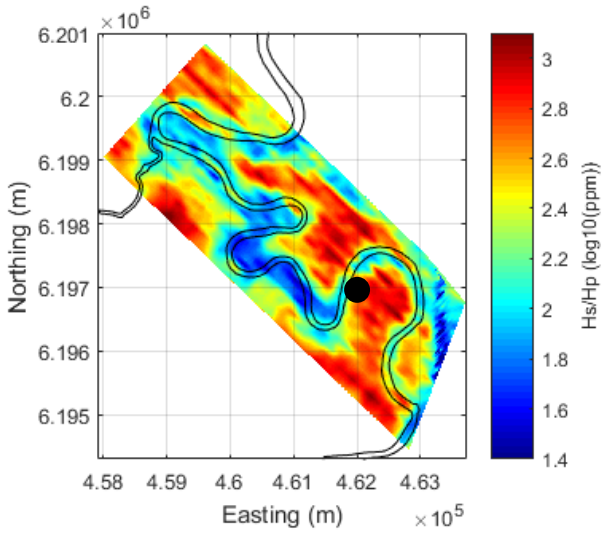
Horizontal Co-planar (HCP) data

In-Phase (Real)

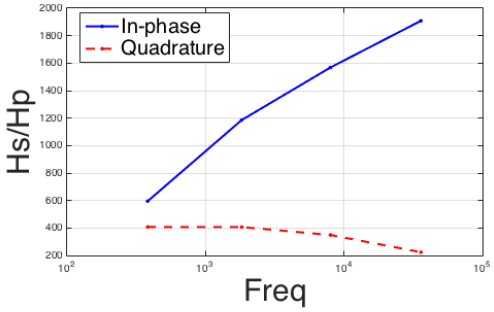
Quadrature (Imaginary)

382 Hz

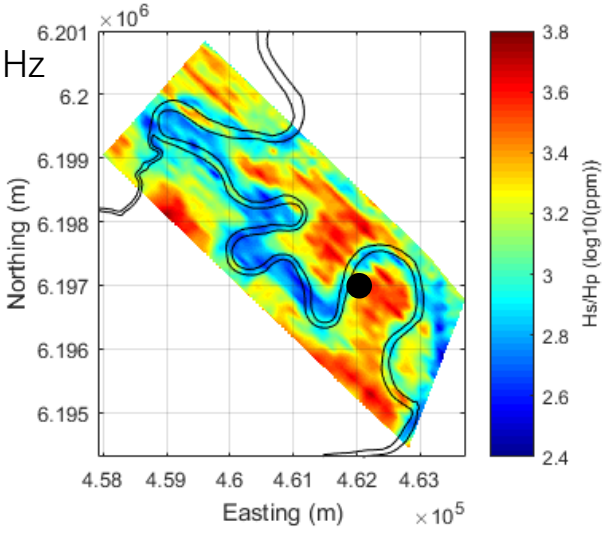


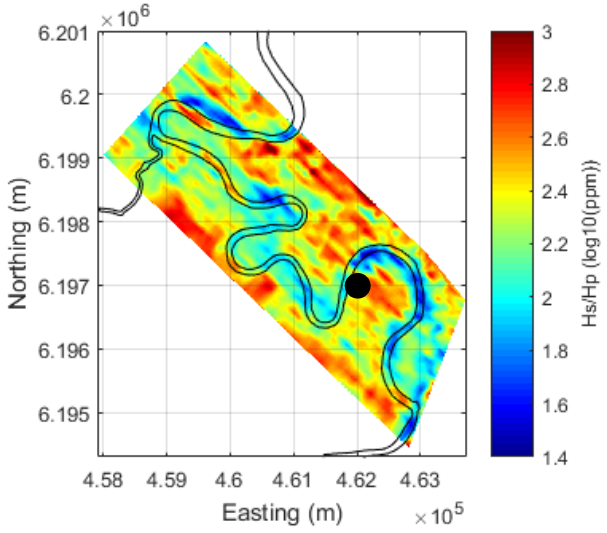


Sounding curve

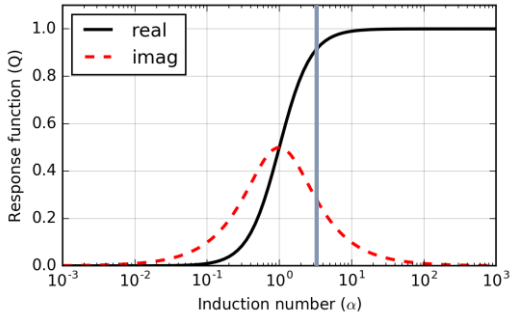


35920 Hz



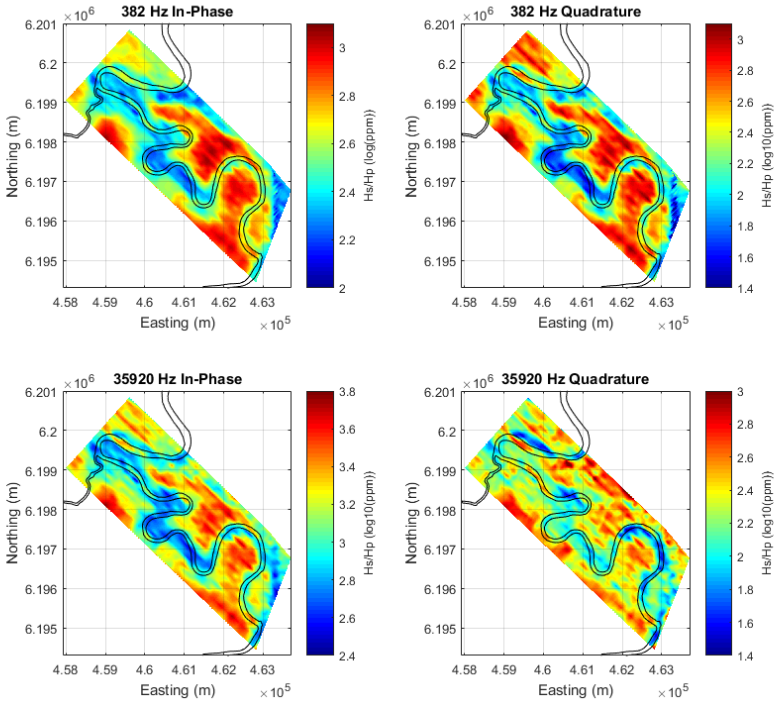


Response curve

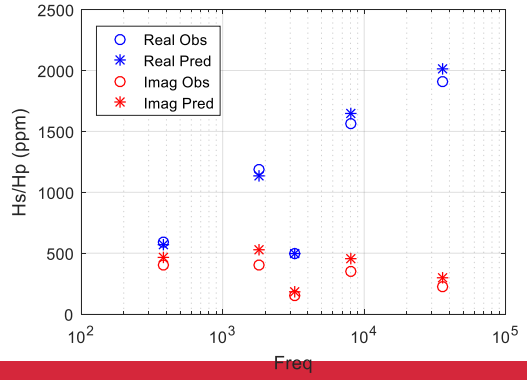


Processing: 1D inversion

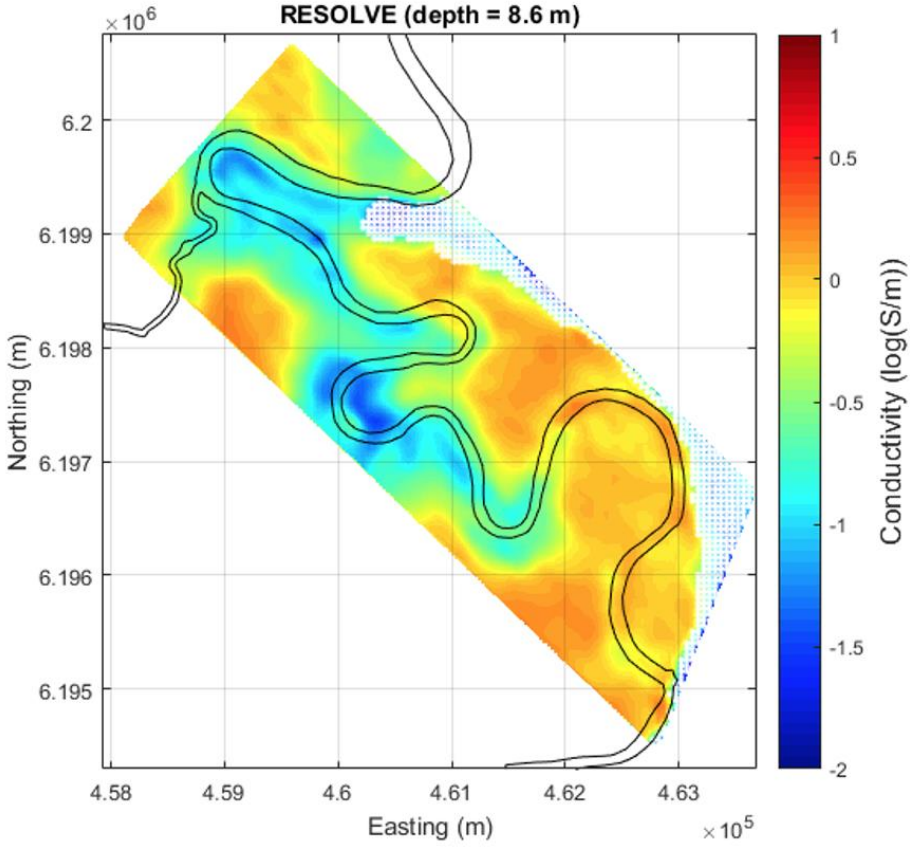
Data



Data fit

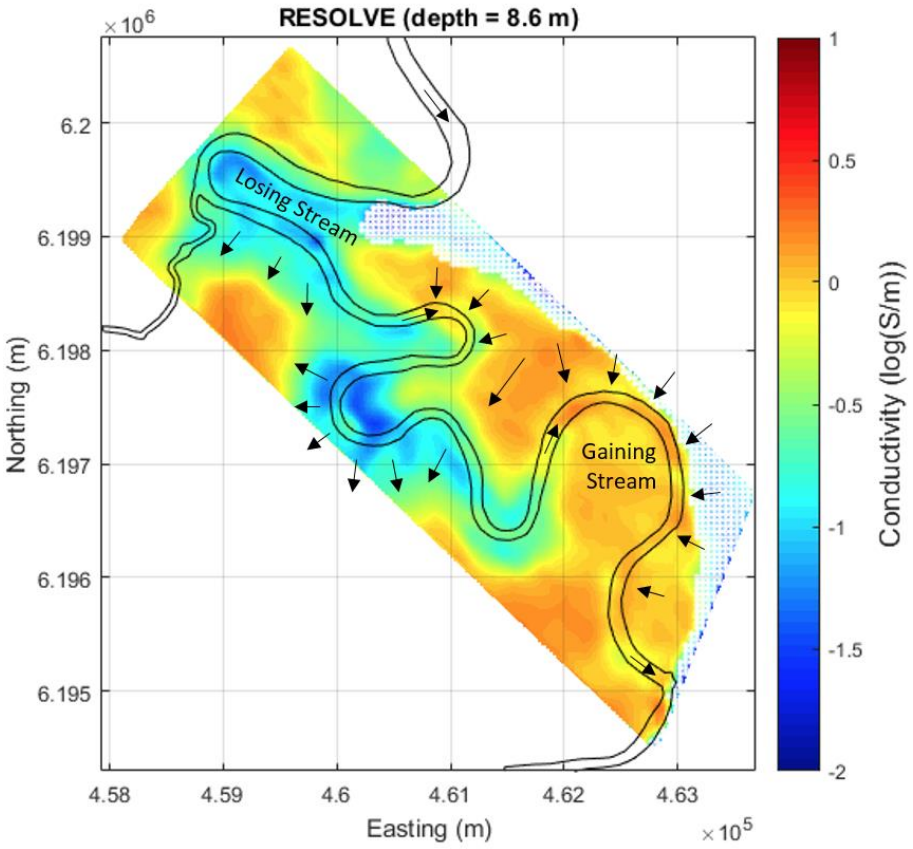


Conductivity model (stitched)

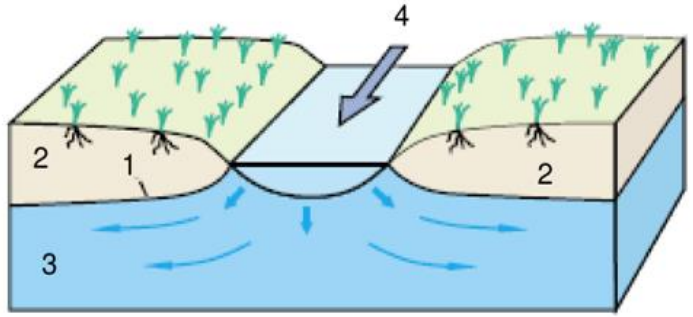


Interpretation

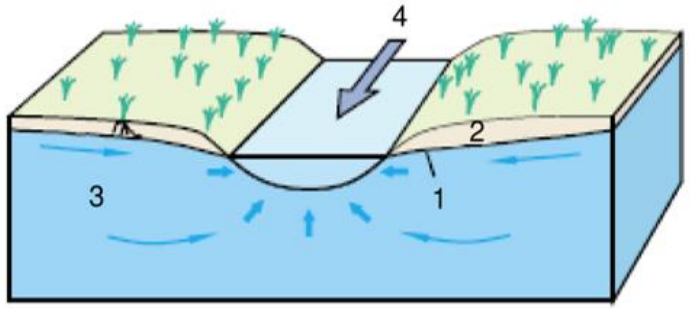
Conductivity model (stitched)



Losing Stream



Gaining Stream

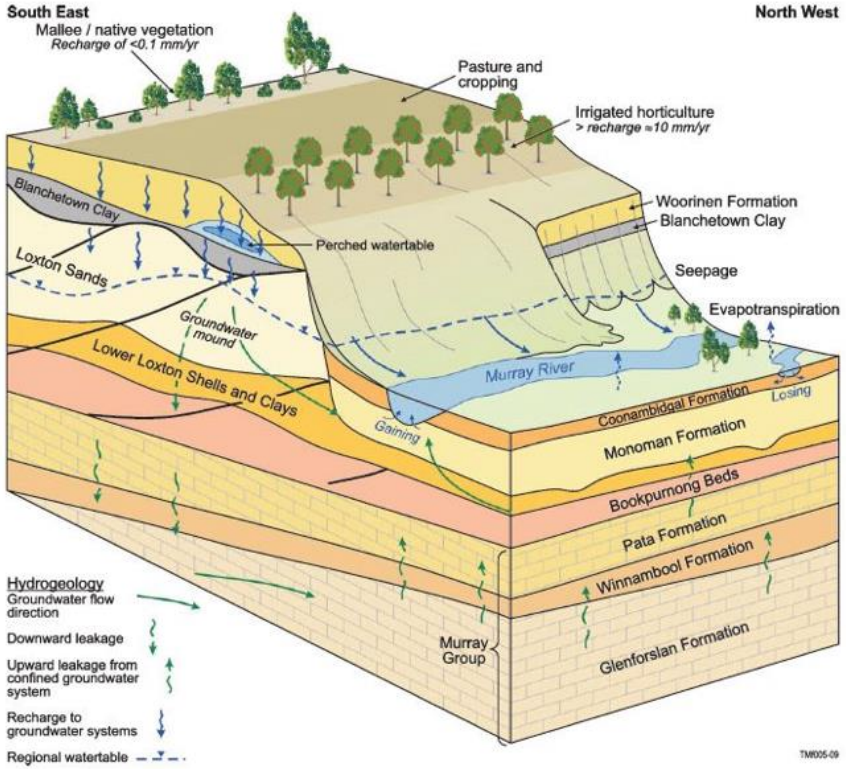


1 – Water table 2 – Unsaturated zone

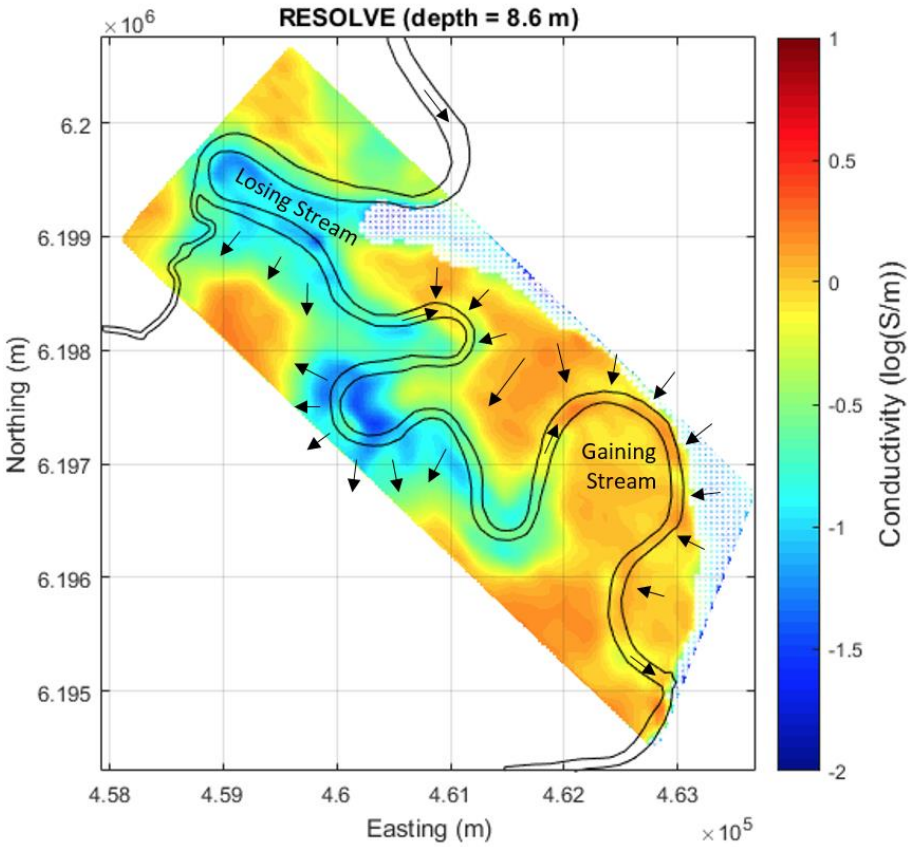
3 – Saturated zone 4 – Flow direction

Synthesis

Hydrological model

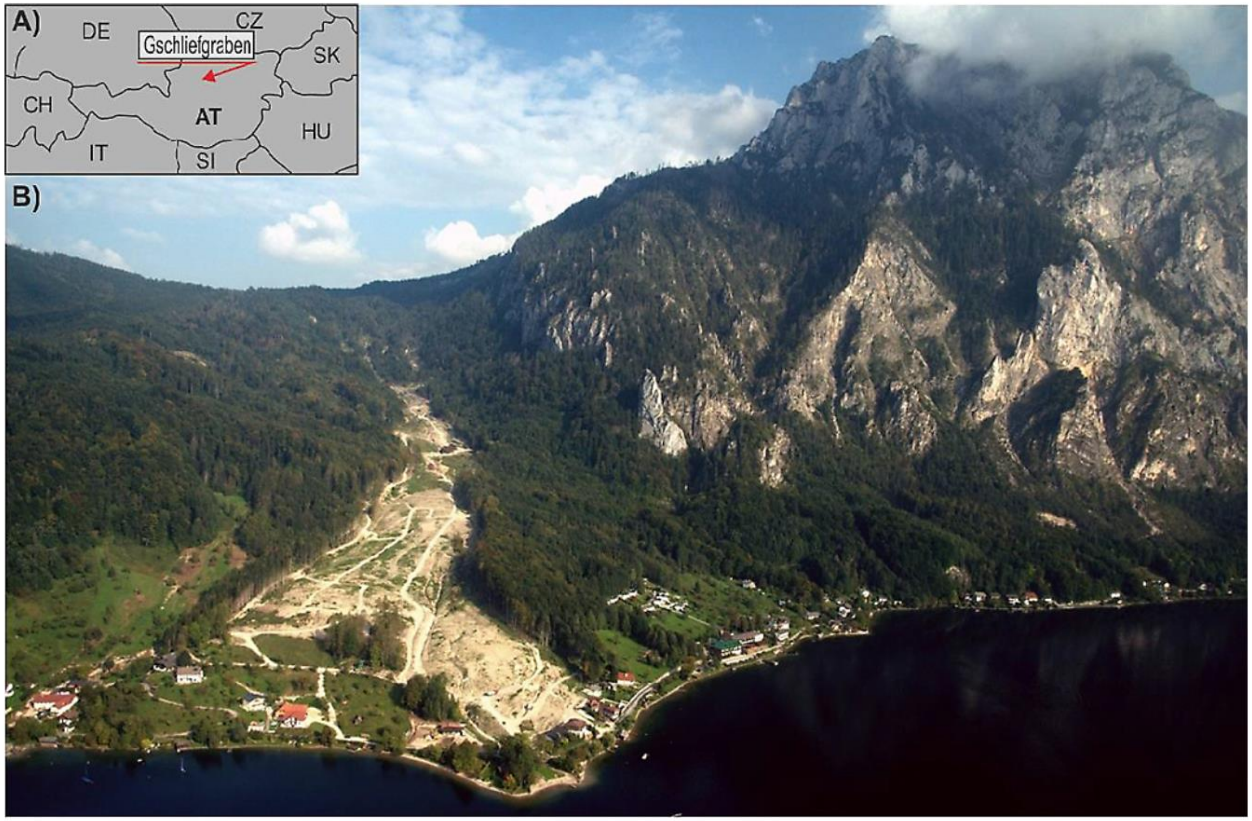


Conductivity model (stitched)



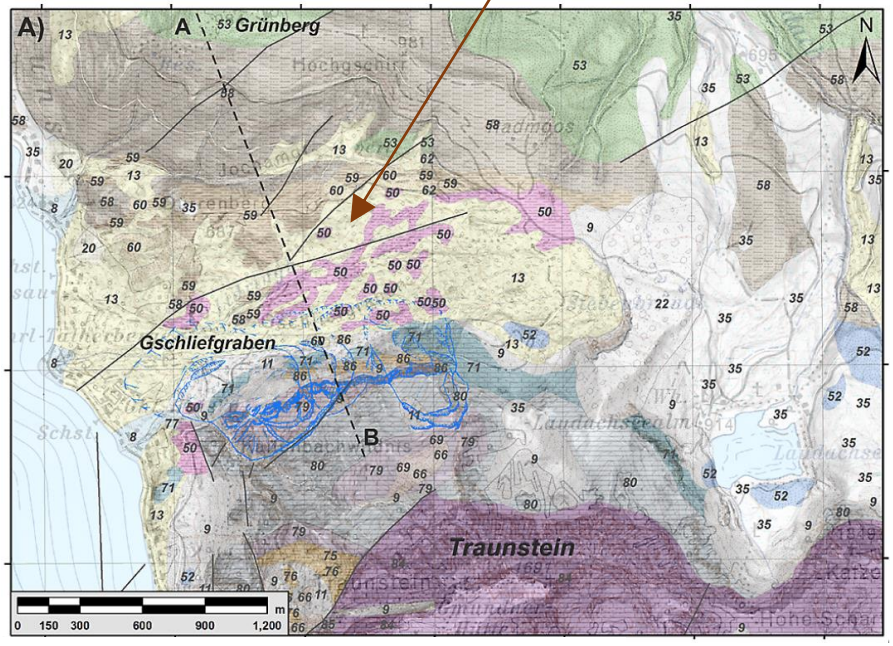
Case History: Airborne geophysical mapping for landslide investigation

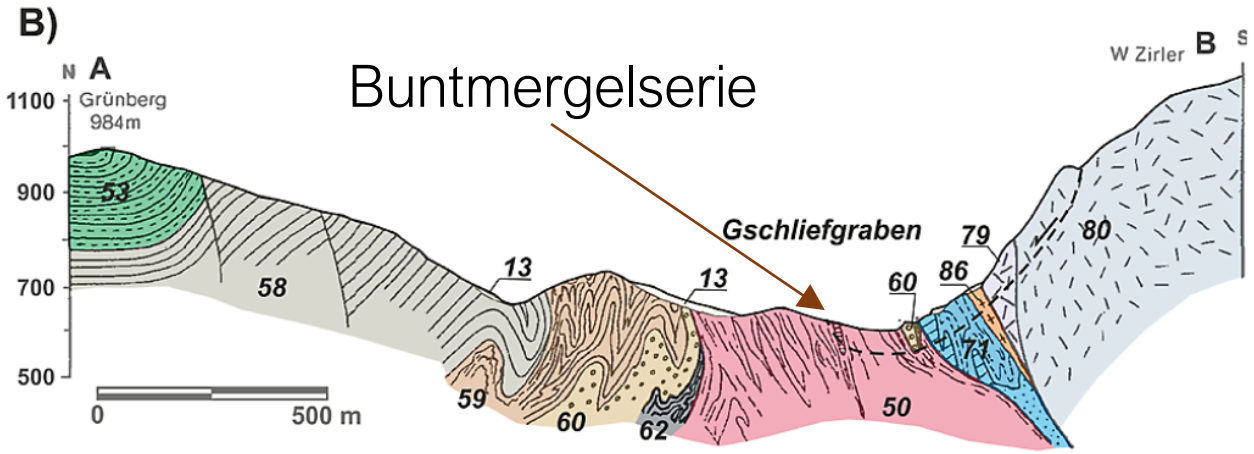
Supper et al., 2013



Setup

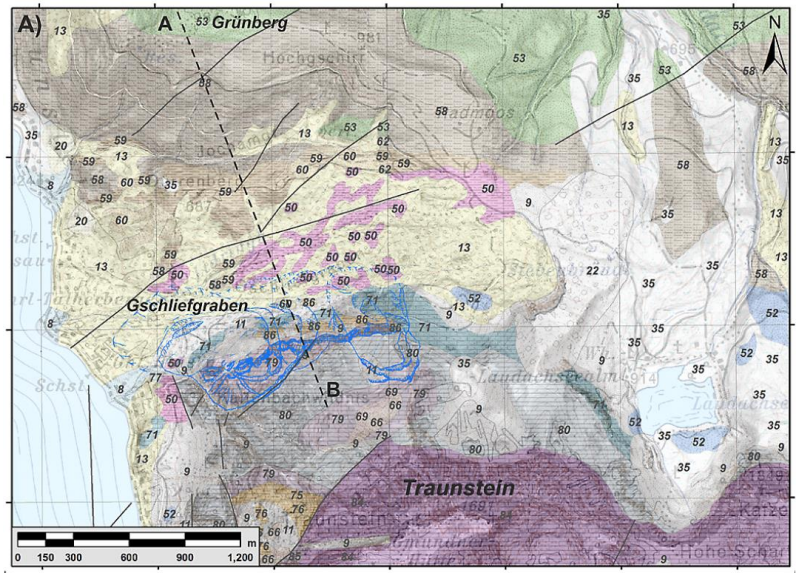
- Gschliefgraben area: most prominent recent landslide of Austria
- Clay layers absorb water → become a plane of weakness and result in a landslide
- SafeLand Project: evaluate airborne geophysics



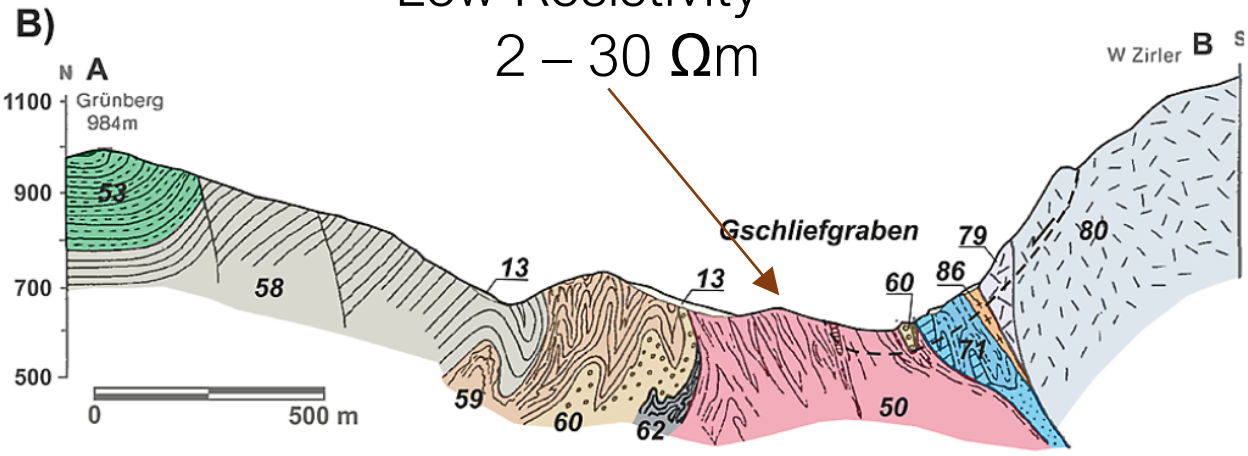


Properties

Deformed variegated marl, claystone, … (target unit)	2 – 30 Ωm
Claystone, marl	50 – 100 Ωm
Intermediate Sandstone	> 150 Ωm

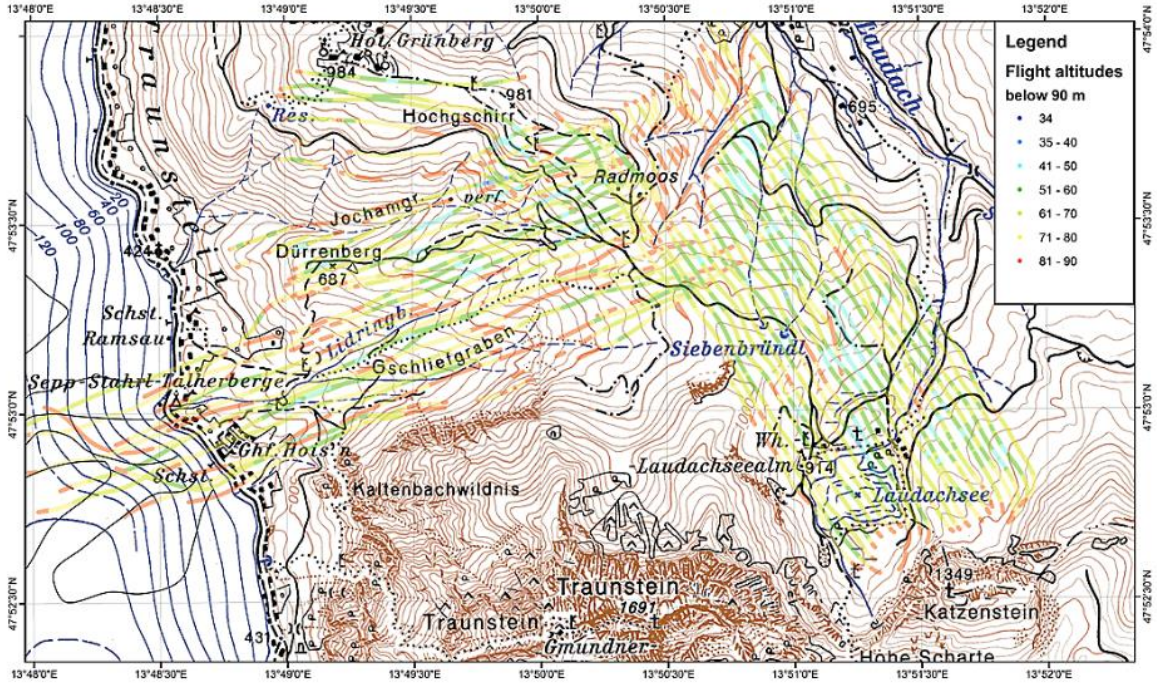


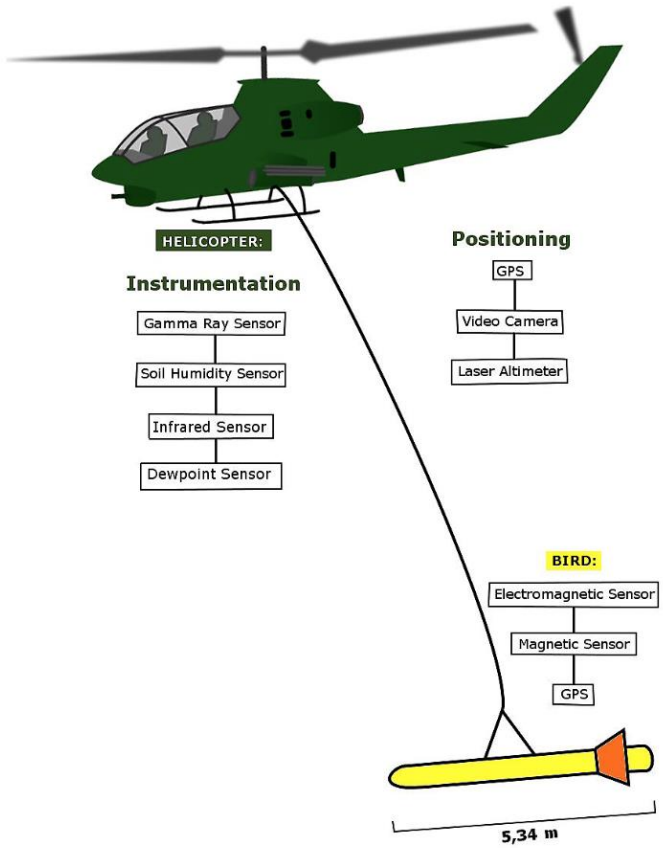
Buntmergelserie
Low Resistivity
2 – 30 Ωm



Survey

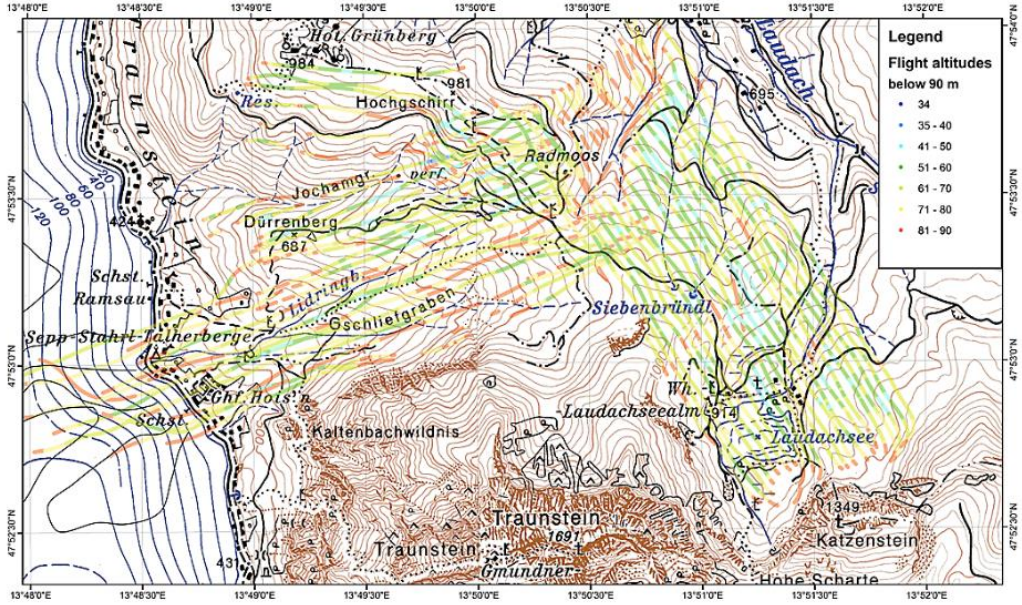
- Multiple airborne sensors
  - **Airborne EM**
  - Gamma Ray
  - Magnetics
  - Passive Microwave

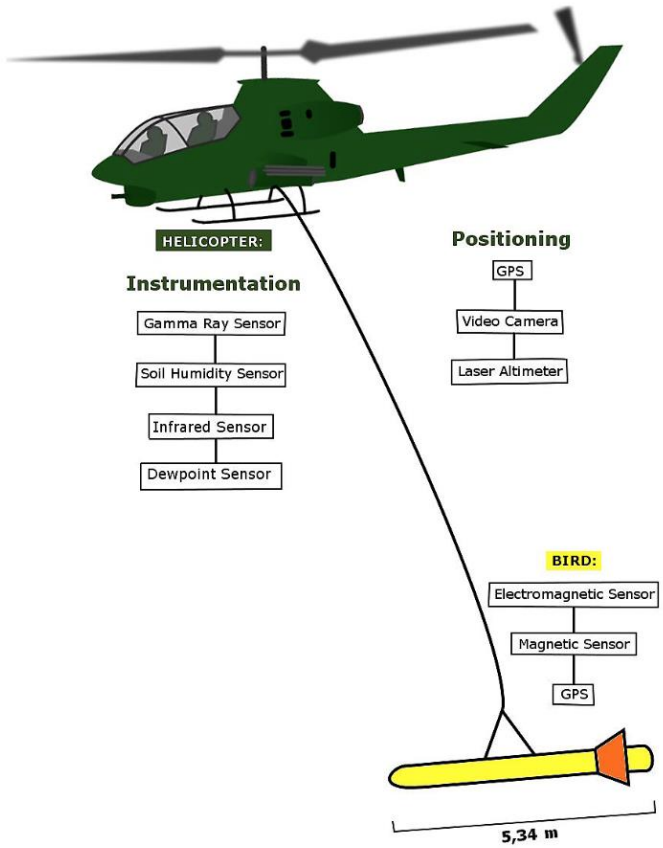




Survey: Airborne EM

- Frequency domain system
  - Frequencies: 340 Hz, 3200 Hz, 7190 Hz and 28 850 Hz
- Sensor height needs to be < 90 m
- Rough topography → flown only uphill (2x flight time)

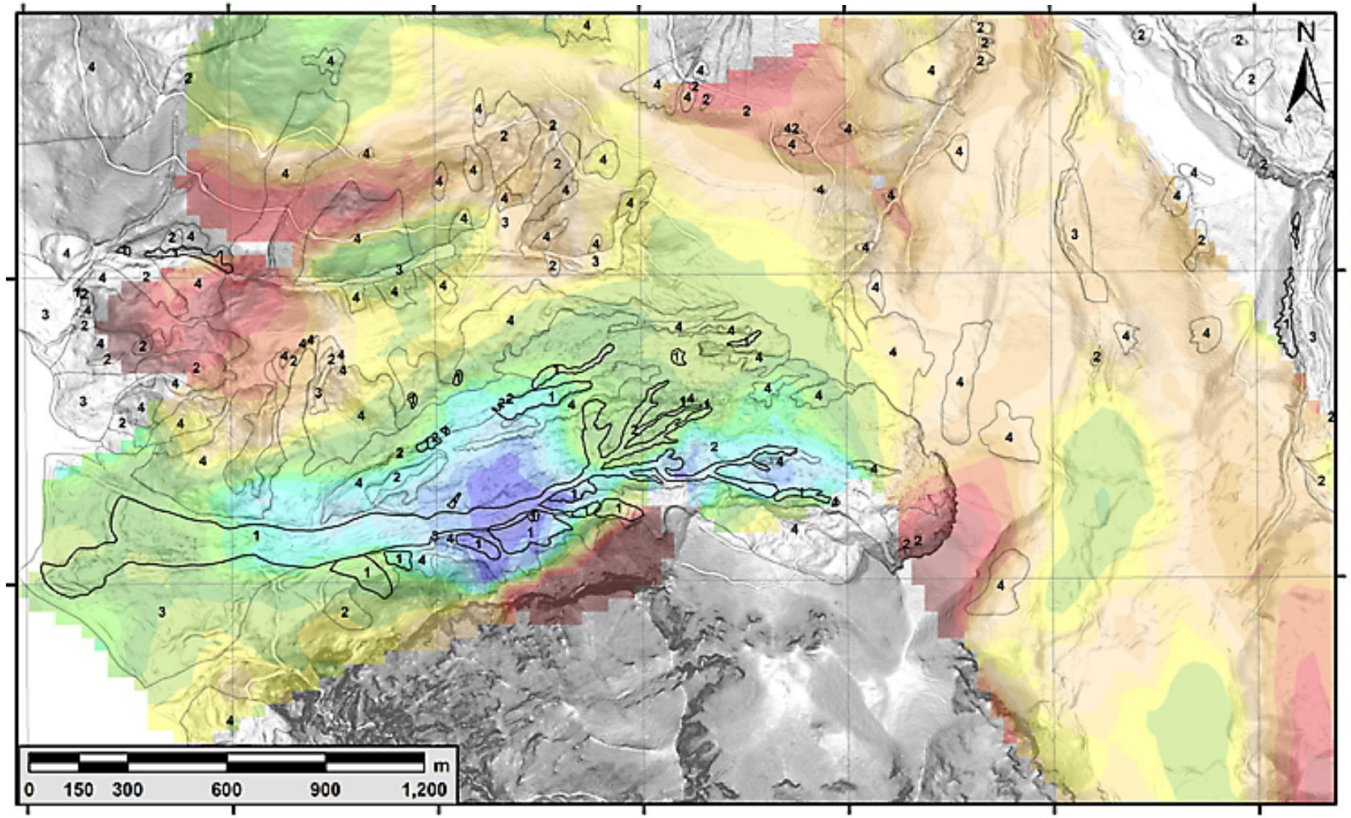




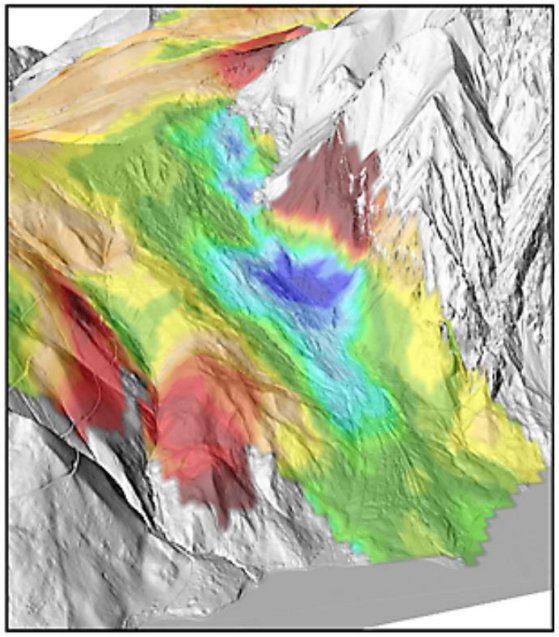
Data & Processing

- Data inverted in 1D

resistivity 0 – 2m below surface



3D view



Legend:

Resistivity [Ohmm]:

2.5 - 5	25.1 - 30	50.1 - 55	120.1 - 135	250.1 - 300
5.1 - 10	30.1 - 35	55.1 - 60	135.1 - 150	300.1 - 350
10.1 - 15	35.1 - 40	60.1 - 75	150.1 - 175	350.1 - 500
15.1 - 20	40.1 - 45	75.1 - 100	175.1 - 200	500.1 - 750
20.1 - 25	45.1 - 50	100.1 - 120	200.1 - 250	750.1 - 1000

Landslide inventory:

1 - active landslides

2 - dormant landslides

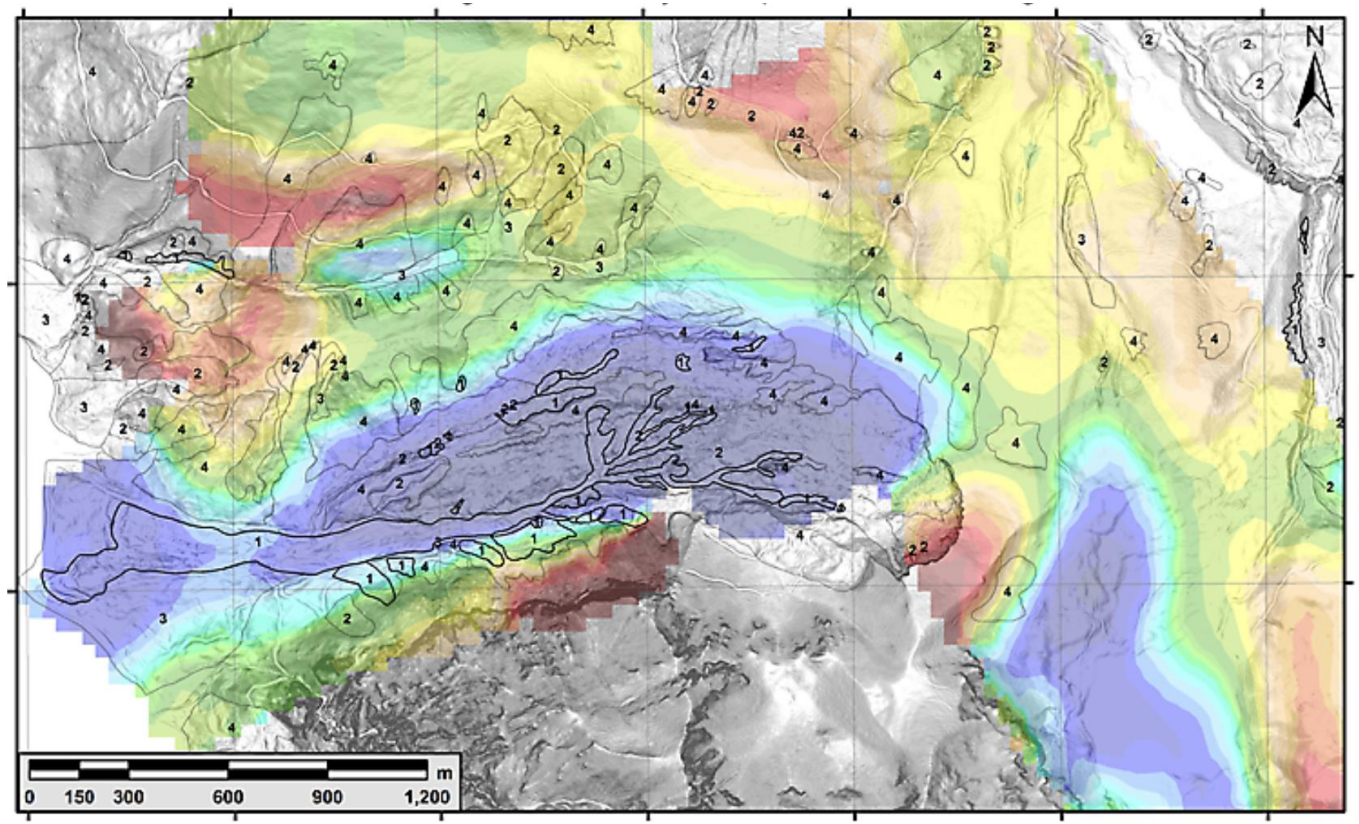
3 - accumulations of inactive earthflows

4 - inactive (old) landslides

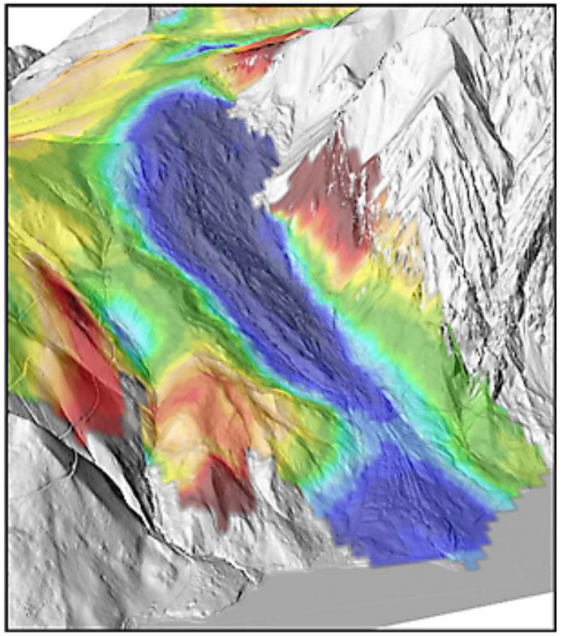
Data & Processing

- Data inverted in 1D

resistivity 20m below surface



3D view



Legend:

Resistivity [Ohmm]:

2.5 - 5	25.1 - 30	50.1 - 55	120.1 - 135	250.1 - 300
5.1 - 10	30.1 - 35	55.1 - 60	135.1 - 150	300.1 - 350
10.1 - 15	35.1 - 40	60.1 - 75	150.1 - 175	350.1 - 500
15.1 - 20	40.1 - 45	75.1 - 100	175.1 - 200	500.1 - 750
20.1 - 25	45.1 - 50	100.1 - 120	200.1 - 250	750.1 - 1000

Landslide inventory:

1 - active landslides

2 - dormant landslides

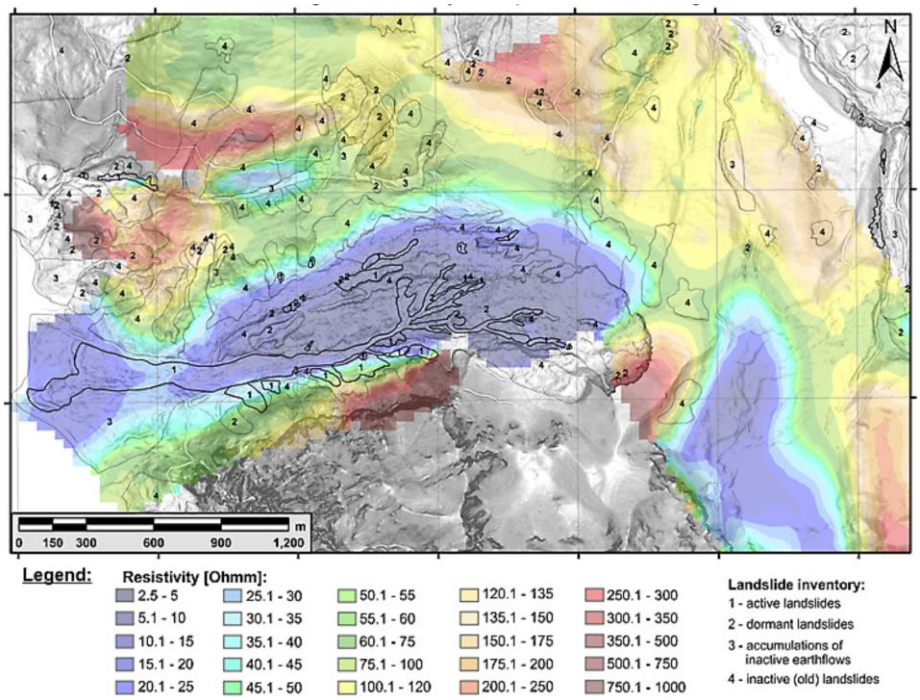
3 - accumulations of inactive earthflows

4 - inactive (old) landslides

Interpretation

- 2 – 30 Ωm contour delineates the Buntmergelserie
  - landslide inventory map shows recent landslides are associated with Buntmergelserie
  - Low resistivities show this is most incompetent unit
- Buntmergelserie: highly tectonised
  - Anti-synclinal fold
  - Strongly west-east dipping axis

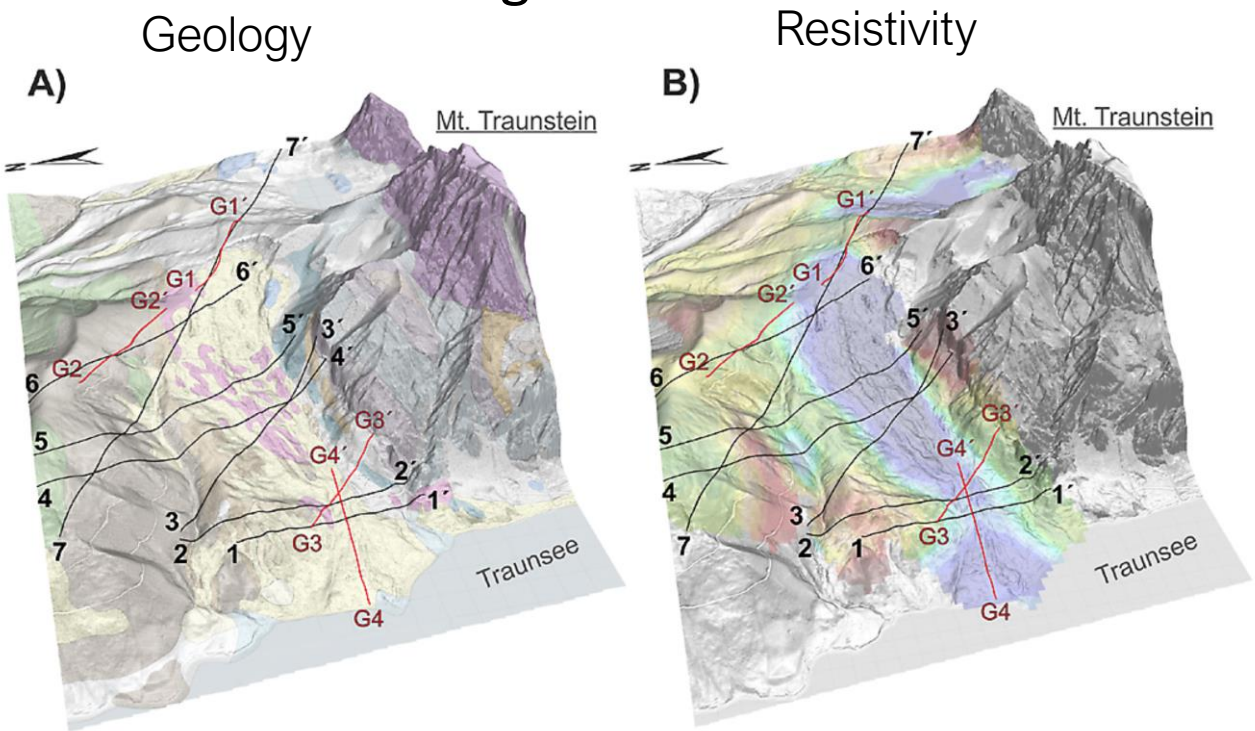
resistivity 20m below surface



Synthesis

- Airborne EM provided better understanding of the spatial and depth structure of geologic units

- Available model for landslides was significantly improved
  - helped to design proper location of sensors for early warning network for the Gschliefgraben area



Week	Date	Topics	Comments
1	08/21 Tues	Lecture: Introduction to electromagnetics	
	08/23 Thur	Lecture: Vector analysis & PDE	
	08/27 Mon		Last day to add a class
2	08/28 Tues	Lecture: static electrical field & DC theory	
	08/30 Thur	Lecture: DC (survey & data)	
3	09/04 Tues	Lecture: DC (applications)	
	09/05 Wed		Last day to drop w/o a grade
	09/06 Thur	Lab: Understanding DC survey and sensitivity	Report due on 09/13 @ 4 PM
4	09/11 Tues	Lecture: complex variables & FFT	
	09/13 Thur	Lecture: review of electrodynamic theory	
5	09/18 Tues	Lecture: RL circuit with DC and AC	
	09/20 Thur	Lecture: RL circuit model of EM induction	
6	09/25 Tues	Lab: RL circuit	Report due on 10/02 @ 4 PM
	09/27 Thur	Lecture: Plane waves in frequency and time domain	
7	10/02 Tues	Lab: plane waves	Report due on 10/09 @ 4 PM
	10/04 Thur	Lecture: Time domain EM (inductive source)	
8	10/09 Tues	Lab: Time domain EM	Report due on 10/16 @ 4 PM
	10/11 Thur	Lecture: Frequency domain EM (inductive source)	
9	10/16 Tues	Form a team & Select a topic for presentation	In-class attendance not required
	10/18 Thur	Literature search & reading	In-class attendance not required
10	10/23 Tues	Lab: Frequency domain EM	Report due on 10/30 @ 4 PM
	10/25 Thur	Lecture: Recap & Review	
11	10/30 Tues	Exam	
	11/01 Thur	Lecture: EM_grounded sources	last day to drop a course with a 'W'
12	11/06 Tues	Lecture: EM_grounded sources	
	11/08 Thur	Lab: EM_grounded sources	Report due on 11/15 @ 4 PM
13	11/13 Tues	Lecture: EM_natural sources	
	11/15 Thur	Lecture: EM_natural sources	
14	11/20 Tues	Lab: EM_natural sources	Report due on 11/27 @ 4 PM
	11/22 Thur	No class due to Thanksgiving	
15	11/27 Tues	Final presentation	
	11/29 Thur	Final presentation	

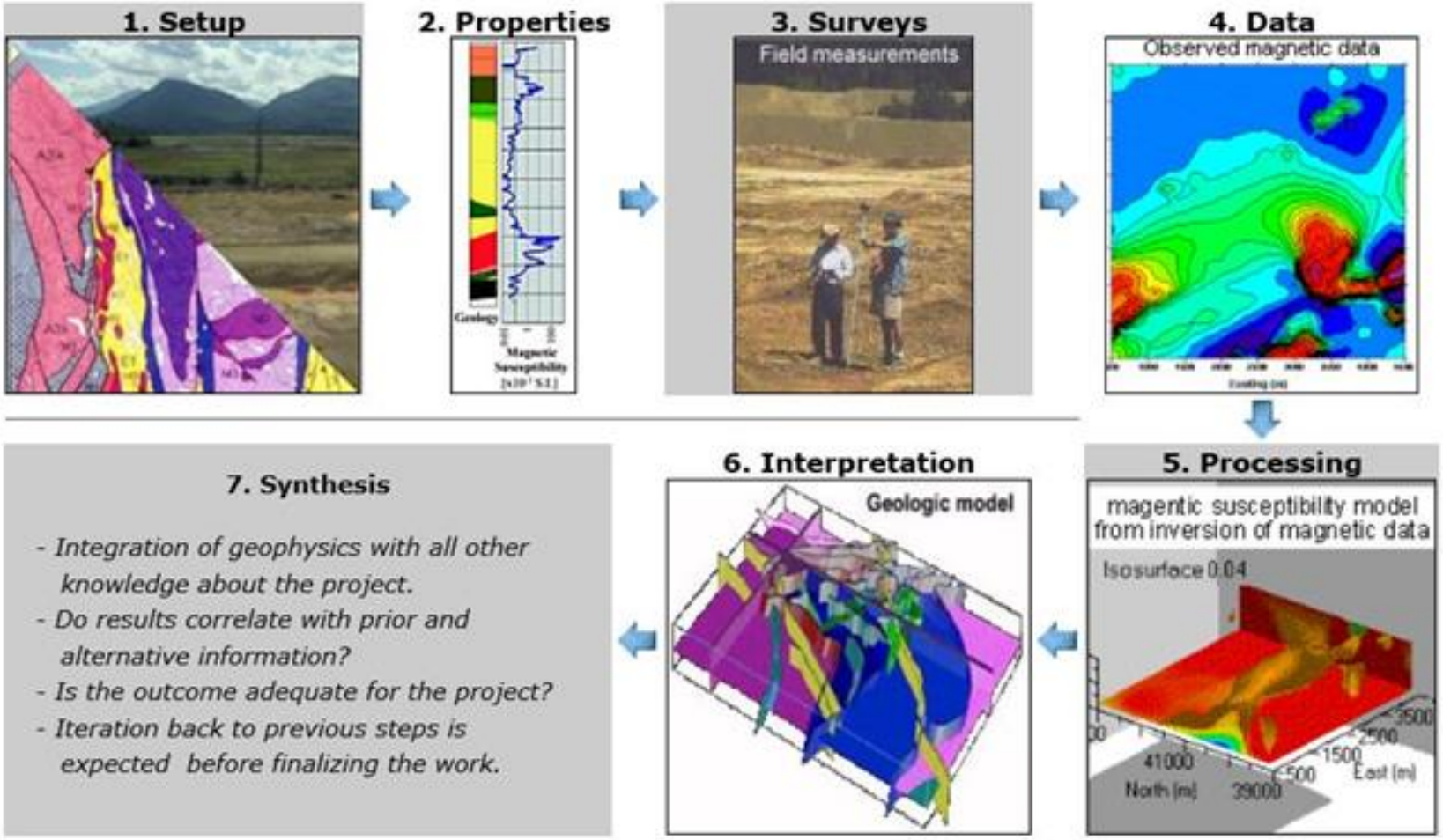
Tasks to accomplish next week

- Find your teammates and form a team
  - Each team consisting of two or three students
- Decide on which EM application to focus on
  - Hydrocarbon
  - Mineral
  - Groundwater/hydrology
  - Engineering & Environmental
  - Geothermal
  - Large scale crustal studies
  - etc.
- Do literature search
  - you might want to do literature search before deciding on EM applications

Tasks to accomplish in the next few weeks

- Do literature search
- Find a few papers on the selected topic
  - Suggested deadline: Oct 30th, 2018
- Read them
- Select one or two to present
  - Suggested deadline: Nov. 15th, 2018
- Final presentation on Nov. 27 & 29th.

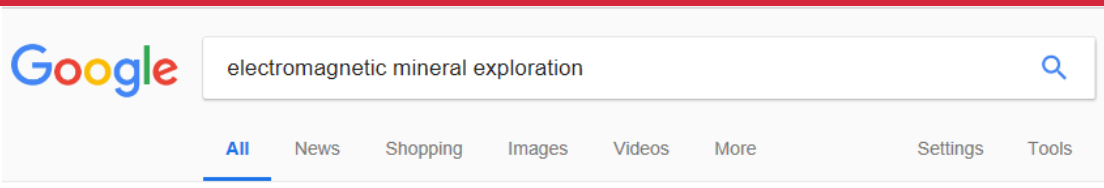
7-step framework for case histories



A few things to do

- Send TA the names of students in your team
- Send TA the topic you would like to focus on.
- By 4 pm on Oct. 23rd, 2018

Literature search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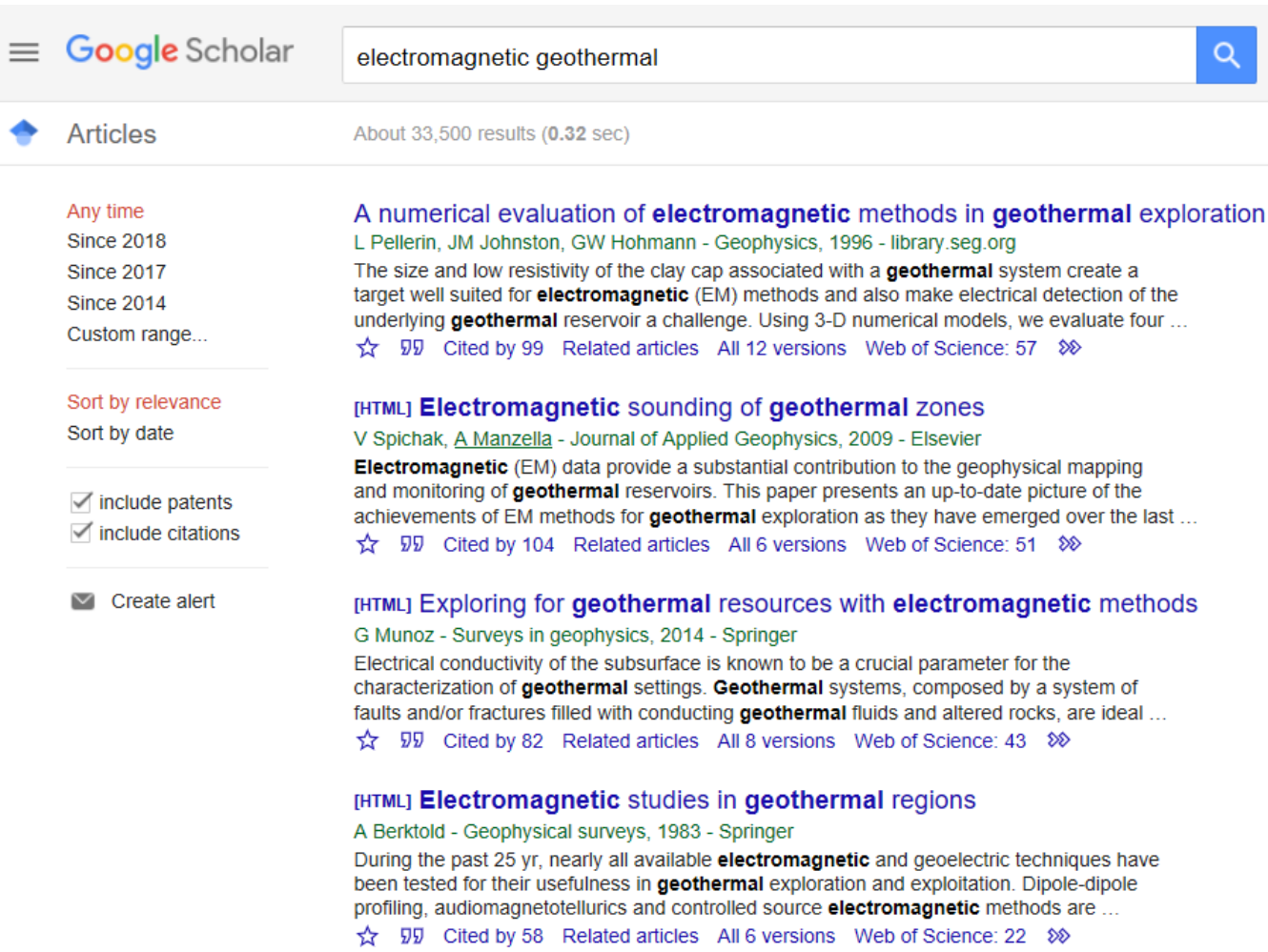
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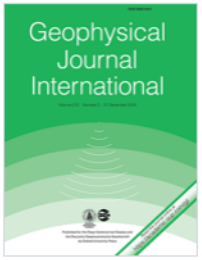

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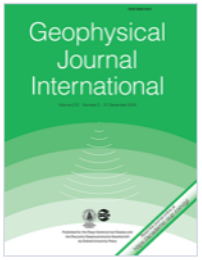

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